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ESTIMATION OF COVARIANCES OF ^{16}O, ^{23}Na, Fe, ^{235}U, ^{238}U AND ^{239}Pu NEUTRON NUCLEAR DATA IN JENDL-3.2

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Estimation of Covariances of ^{16}O, ^{23}Na, Fe, ^{235}U, ^{238}U and ^{239}Pu Neutron Nuclear Data in JENDL-3.2

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Covariances of nuclear data have been estimated for 6 nuclides contained in JENDL-3.2. The nuclides considered are ^{16}O, ^{23}Na, Fe, ^{235}U, ^{238}U, and ^{239}Pu, which are regarded as important for the nuclear design study of fast reactors. The physical quantities for which covariances are deduced are cross sections, resolved and unresolved resonance parameters, and the first order Legendre-polynomial coefficient for the angular distribution of elastically scattered neutrons. As for ^{235}U, covariances were obtained also for the average number of neutrons emitted in fission. The covariances were estimated by using the same methodology that had been used in the JENDL-3.2 evaluation in order to keep a consistency between mean values and their covariances. The least-squares fitting code GMA was used in estimating covariances for reactions of which JENDL-3.2 cross sections had been evaluated by taking account of measurements. In nuclear model calculations, the covariances were calculated by the KALMAN system. The covariance data obtained were compiled in the ENDF-6 format, and will be put into the JENDL-3.2 Covariance File which is one of JENDL special purpose files.

Keywords: Covariance, Nuclear Data, JENDL-3.2, ^{16}O,^{23}Na, Fe, ^{235}U, ^{238}U, ^{239}Pu, Cross Section, Resonance Parameter, Angular Distribution

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ＪＥＮＤＬ-3.2に収納されている中性子核データ ^{16}O、^{23}Na、Fe、^{235}U、^{238}U、^{239}Puの共分散の推定

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（1997年９月19日受理）

ＪＥＮＤＬ-3.2に収納されている６核種の核データの共分散を推定した。対象となった核種は高速炉の核設計研究で重要な、^{16}O、^{23}Na、Fe、^{235}U、^{238}U 及び ^{239}Puである。共分散が求められた物理量は、断面積、分離・非分離共鳴パラメータ及び弾性散乱における１次のルジャンドル展開係数である。^{235}Uに関しては、核分裂における平均中性子発生数の共分散も求められた。共分散推定においては、ＪＥＮＤＬ-3.2の評価に用いられたのと同じ方法が用いられた。ＪＥＮＤＬ-3.2で与えられている反応断面積が実験値を基に求められた場合は、最小自乗フィッティングコードＧＭＡを用い共分散を推定した。一方、理論計算値の共分散はＫＡＬＭＡＮシステムにより計算した。ここで得られた共分散データはＥＮＤＦ-６フォーマットでファイル化され、ＪＥＮＤＬ特殊目的ファイルの１つであるＪＥＮＤＬ-3.2共分散ファイルに収納される。

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1. Introduction

Uncertainties in nuclear data are needed not only to estimate margins in design and safety of nuclear facilities, but also to adjust group constants by considering critical experiments. The Nuclear Data Center of the Japan Atomic Energy Research Institute (JAERI) has been involved in preparing the integrated group cross section library promoted by the Power Reactor and Nuclear Fuel Development Corporation (PNC).

In the present work, we estimated covariances of nuclear data for ^{16}O, ^{23}Na, Fe, ^{235}U, ^{238}U, and ^{239}Pu contained in JENDL-3.2. The physical quantities for which covariances were estimated are cross sections, resolved and unresolved resonance parameters, and the 1st order Legendre-polynomial coefficient for the elastic angular distributions of neutrons. As for ^{235}U, covariances were obtained also for the average number of neutrons emitted in fission.

The covariances were estimated on the basis of the same methods which had been taken in the JENDL-3.2 evaluation[1]. The least-squares fitting code GMA[2], which was developed at the Argonne National Laboratory, was applied to estimate covariances when the JENDL-3.2 data had been obtained by fitting to available experimental data. In cases where the JENDL-3.2 data are based on nuclear model calculations, the code system KALMAN[3], which was developed at Kyushu University, was used to deduce uncertainties in model parameters. Then, the covariances of the model calculations were obtained by using the law of error propagation. On the KALMAN system, one can get covariances of cross sections and angular distributions of emitted neutrons calculated from the optical model code ELIESE-3[4], the statistical model codes CASTHY[5] and EGNASH[6], and the coupled-channel code ECIS[7].

In JENDL-3.2, the fission cross sections of ^{235}U, ^{238}U, and ^{239}Pu were obtained by the simultaneous evaluation[8] which took account of absolute and ratio measurements. The simultaneous evaluation yielded covariances as well as average cross sections although the covariances were not compiled into JENDL-3.2. In the present work, we adopted the results obtained by the simultaneous evaluation without any modification.

In this report, we describe the methods of covariance estimation taken for each nuclide together with the results obtained.

2. Oxygen-16

Covariances were estimated for the total, inelastic scattering, (n,2n), (n,nα), (n,np), (n,d), (n,γ), (n,p), and (n,α) cross sections and for the 1st order Legendre coefficient for the elastic angular distribution of neutrons. In general, the elastic scattering cross section is obtained by subtracting partial cross sections from the total cross section. In such a case, an "NC-type sub-subsection" is used to represent covariances in the ENDF-format[9] instead of actually estimating the covariance of the elastic scattering cross section. Following this procedure, an "NC-type sub-subsection" was made in the data file for ^{16}O, and the covariance of the elastic scattering cross section can be calculated from those of other cross sections. The same procedure was applied to the covariances of the elastic scattering cross sections for other nuclides in the present work.

2.1 Covariance Estimation Based on Measurements

1) Total cross section

The GMA code was applied to estimate the covariance from the two sets of measurements: Cierjacks et al.[10] and Larson[11]. It is found from Figs. 1 and 2 that the estimated error is consistent with the measurements and looks quite reasonable.

2) (n,2n) reaction cross section

The covariances were obtained from the measurements of Brill et al.[12] In JENDL-3.2, the cross section is ten times as large as the measurements because of a compilation mistake. Therefore, the error was enlarged to cover the correct cross section values.

3) (n,nα) and (n,np) reaction cross sections

The JENDL-3.2 evaluation is based on nuclear model calculations since there exists no measurement. However, the parameters required as input to the model code are no longer available. Therefore, in the present work, we used the following rule obtained by Oh[13] :

Cross section σ (mb)	Standard deviation (%)
500<σ	5
100≤σ≤500	10
1≤σ≤100	15
σ<1	>25

A full correlation was assumed since the JENDL-3.2 data were obtained from nuclear model calculations and a strong correlation was expected in such calculations.

4) (n,d) reaction cross section

The covariances were obtained on the basis of the measurements of Lillie[14]. The result is shown in Fig. 3.

5) (n,γ) reaction cross section

The covariances were estimated from the measurements of Wüst et al.[15] and Igashira et al.[16] The result is shown in Fig. 4.

6) (n,p) reaction cross section

The covariances were estimated from the measurements of Borman et al.[17], DeJuren and Stooksberry[18], Seeman and Moore[19], and Martin[20]. The result is shown in Fig. 5.

7) (n,α) reaction cross section

The covariances were estimated from the following experimental data:

Nordborg et al.[21], Davis et al.[22], Sick et al.[23], Divatia et al.[24], Dickens and Perey[25], Orphan et al.[26] and Bair and Haas[27].

The result is shown in Fig. 6. In the energy region above 7 MeV, experimental data are discrepant with each other.

2.2 Covariance Estimation Based on Nuclear Model Calculations

1) Inelastic scattering cross section

The CASTHY code yielded the covariances of the inelastic scattering cross section using the KALMAN system. The measurements of Nordborg et al.[21] were used to deduce the uncertainties in the model parameters.

2) Angular distributions for the elastic scattering

In JENDL-3.2, the angular distributions of elastically scattered neutrons were

evaluated in the following way:

10^{-5} eV – 3 MeV, 5 MeV – 9 MeV:	Resonance theory
3 MeV – 5 MeV:	Measurements[28]
9 MeV – 15 MeV:	Measurements[29]
15 MeV – 20 MeV:	Optical model calculations.

The covariances of the 1st order Legendre coefficient were estimated on the basis of the same method that had been taken in the JENDL-3.2 evaluation. In the energy region where the resonance theory was adopted, a standard deviation of 10% was assumed for the neutron width by considering available experimental data, and then the covariances of the Legendre coefficient were calculated by using the law of error propagation. The optical model code ELIESE-3 was used to calculate the covariances above 15 MeV.

3. Sodium-23

Covariances were obtained for the total, inelastic scattering, (n,2n), (n,nα), (n,np), (n,γ), (n,p), (n, α) reaction cross sections, resolved resonance parameters, and the 1st order Legendre coefficient for the elastic scattering.

3.1 Covariances of Resonance Parameters

In JENDL-3.2, resolved resonance parameters are given below 350 keV. The data were taken from the compilation of Mughabghab et al.[30] In the present work, we adopted those uncertainties in resonance energy, neutron width, and capture width which were recommended by Mughabghab et al. However, as for the negative resonance, the relative errors of 0% and 1% were assumed for the neutron and capture widths, respectively, by considering the reproducibility of the thermal cross sections.

3.2 Covariances Based on Measurements

1) Total cross section

The GMA code was applied to estimate the covariances from the measurements of Cieljacks et al.[31], Langsford et al.[32], Stoler et al.[33], and Larson et al.[34] The results are shown in Figs. 7 and 8.

2) (n,2n) reaction cross section

The GMA code was applied to estimate the covariances of the cross section. The following measurements were taken into account:

Prestwood[35], Menlove et al.[36], Barral et al.[37], Maslov et al.[38], Araminowicz et al.[39], Sigg[40], Shani[41], Adamski et al.[42], and Xu Zhi-Zheng et al.[43]

Figure 9 shows the JENDL-3.2 values and their uncertainties. In the figure, there exist two groups of measurements above 14.5 MeV. It should be noted that the lower group was recognized to represent the correct cross sections for this reaction.

3) (n,γ) reaction cross section

In JENDL-3.2, this reaction cross section was evaluated by using the statistical model code CASTHY. However, the parameter values used in the evaluation are no longer available, and our CASTHY calculations could not reproduce the JENDL-3.2 data. Thus, in the present work, we estimated the covariance of the cross section by applying the GMA code. The following twenty-one data sets were used in fitting:

Cocking et al.[44], Macklin et al.[45], Perkin et al.[46], Leipunskij et al.[47], Kononov et al.[48], Booth et al.[49], Jowitt et al.[50], Bame et al.[51], Lyon et al.[52], Meadows et al.[53], Macklin et al.[54], Rigoleur et al.[55], Csikai et al.[56], Menlove et al.[57], Hasan et al.[58], Ryves et al.[59], Yamamuro et al.[60], Holub et al.[61], Sigg[40], and Magnusson et al.[62]

The result is shown in Fig. 10. The correlation obtained is not so strong since there are few experimental data sets which cover a wide energy range.

4) (n,p) reaction cross section

The GMA code was applied to estimated the covariances. The following measurements were used:

Paul et al.[63], Khirana et al.[64], Mukjerjee et al.[65], Williamson[66], Khurana et al.[67], Picard et al.[68], Mitra et al.[69], Bass et al.[70], Prasad et al.[71], Csikai et al.[56], Flesch et al.[72], Pasquarelli[73], Schantal[74], Bartle[75], Weigmann et al.[76], and Peplink et al.[77]

The result is shown in Fig. 11. In the low energy region, the relative standard deviation is 2-6% except for the threshold energy (13%). The estimated uncertainties look reasonable in the whole energy region.

5) (n,α) reaction cross section

The GMA code was applied to estimate the covariances. The following

measurements were used:

Mukherjee et al.[65], Bizzeti et al.[78], Picard et al.[68], Bass et al.[70], Woelfer et al.[79], Fleshi et al.[72], Bartle[75], Ngoc et al.[80], Weigmann et al.[76], Leich et al.[81], and Sanchez et al.[82]

The result is shown in Fig. 12.

3.3 Covariances Based on Nuclear Model Calculations

1) Inelastic scattering cross section

The statistical model code CASTHY was used to estimate the covariances by using the KALMAN system. The uncertainties in the model parameters were derived by fitting to the following measurements:

Freeman et al.[83], Shipley et al.[84], Towel et al.[85], Glazkov et al.[86], Chien et al.[87], Fasoli et al.[88], Perey et al.[89], Coles et al.[90], and Schweitzer et al.[91]

2) (n,nα) and (n,np) reaction cross sections

The statistical model code EGNASH was used to estimate the covariances of the cross sections. The uncertainties in the model parameters were obtained from the measurements on the (n,p), (n,α), (n,np), and (n,nα) reactions. The measurements on the (n,p) and (n,α) reactions mentioned in Sec. 3.2 were taken into account together with those of Leich et al.[81] for the (n,np) reaction and of Woelfer et al.[79] for the (n,nα) reaction. The standard deviations of the (n,nα) and (n,np) cross sections are shown in Figs. 13 and 14, respectively.

3) Angular distributions for the elastic scattering

The covariances of the 1st order Legendre coefficient were calculated by using the optical model code ELIESE-3 on the KALMAN system. The standard deviation of the coefficient is shown in Fig. 15.

4 Natural Iron

A covariance file for natural iron was produced in the present work. The JENDL-3.2 data for natural iron were made from the isotopic data except the total cross section which was obtained from experimental data on the natural element. The

contribution of minor isotopes (^{54}Fe, ^{57}Fe, and ^{58}Fe) to the covariance for the natural element is quite small since the weight for each isotope is the square of the isotopic abundance. Therefore, the covariances for the most abundant ^{56}Fe were estimated except for the total cross section.

4.1 Covariances of Resonance Parameters

In JENDL-3.2, resolved resonance parameters for ^{56}Fe are given until 250 keV with the multi-level Breit-Wigner formula. The JENDL-3.2 evaluation is based on the analysis by Perey et al.[92] In the present work, the covariances of the resonance parameters were mainly taken from the same analysis. The details are given in a previous report[93].

4.2 Covariances Based on Measurements

1) Total cross section

There exist a lot of experimental data on elemental iron. The GMA code was applied to estimate the covariances from the measurements of Carlson and Cerbone[94], Cierjacks et al.[95], Perey et al.[96], Pattenden et al.[97], and Schwartz et al.[98] Figures 16 and 17 show the estimated standard deviations. Below 3 MeV, the uncertainties are large because of resonance structure.

2) (n,p) reaction cross section

The GMA code was applied to estimate the covariances from the experimental data on the ^{56}Fe(n,p) reaction. The measurements used are given as follows:

Terrel et al.[99], Bormann et al.[100], Santry and Butler[101], Liskien and Paulsen[102], Smith and Meadows[103], Ryves et al.[104], Ikeda et al.[105], and Li et al.[106]

Figure 18 shows the result.

4.3 Covariances Based on Nuclear Model Calculations

1) Inelastic scattering and (n,γ) reaction cross sections

The CASTHY code was used to estimate the covariances. The following measurements for ^{56}Fe were used to derive the uncertainties in the model parameters:

<u>Inelastic scattering</u>:

Smith and Guenther[107], Hopkins and Gilbert[108], Benjamin et al.[109], and Kinney

and Perey[110].

(n, γ) reaction:

Huang et al.[111] and Allen et al.[112]

Figure 19 shows the result of the (n, γ) reaction on the natural element. It is found from the figure that the JENDL-3.2 values are much smaller than measured values above 10 MeV since the direct capture was not considered in the evaluation. Therefore, the differences between the JENDL-3.2 cross sections and those calculated by using a systematics[113], which reasonably reproduces measured values, were given as the uncertainties above 10 MeV.

2) (n,2n), (n,nα), (n,np), (n,d), (n,t), and (n, α) reaction cross sections

The EGNASH code was used to estimated the covariances. The covariances of the model parameters were obtained by considering experimental data on the (n,2n) and (n,p) reactions. The measurements for the (n,p) reaction on ^{56}Fe were mentioned in Sect. 4.2, while those for the (n,2n) reaction on ^{56}Fe are given as follows:

Wenusch and Vonach[114], Corcalciuc et al.[115], and Frehaut et al.[116]

Figures 20 and 21 show the standard deviations obtained for the (n,2n) and (n, α) reactions on the natural element, respectively.

3) Angular distributions for the elastic scattering

The ELIESE-3 code was used to estimate the covariances of the 1st order Legendre coefficient for the elastic scattering. The uncertainties in the optical model parameters were obtained by considering the experimental data on the total cross section mentioned in Sect. 4.2. Figure 22 shows the estimated relative standard deviation.

5 Uranium-235

Covariances were obtained for the total, inelastic scattering, (n,2n), (n,3n), (n,4n), and (n,γ) reaction cross sections, unresolved resonance parameters, average number of neutrons emitted in fission, and the 1st order Legendre coefficient for the elastic scattering.

5.1 Covariances of Resonance Parameters

In JENDL-3.2, resolved resonance parameters are given in the energy region below 500 eV, while unresolved ones are given in the range from 500 eV to 30 keV. The resolved resonance parameters in the Reich-Moore type were taken from ENDF/B-VI.2. However, the covariances of the parameters are not available at the Oak Ridge National Laboratory, where the evaluation[117] for ENDF/B-VI.2 was done. Therefore, in the present work, we gave up making the covariances of the parameters since it was almost impossible to deduce them independently. In the next version JENDL-3.3, we will probably adopt the latest resonance parameters obtained by Leal et al.[118], and their estimated covariances may be compiled into JENDL-3.3.

The unresolved resonance parameters in JENDL-3.2 were obtained by fitting to experimental data on the total, capture, and fission cross sections with the ASREP[119] code. The initial average parameters required as input to the code were taken from the compilation of Mughbghab[120]. In the present work, the standard deviations of the average parameters such as a capture width Γ_γ, a level spacing D, s- and p-wave strength functions S_0, S_1 were estimated on the basis of the work of Mughabghab. The uncertainty in the fission width Γ_f was determined form its energy dependence in the range of 500 eV to 30 keV. The relative standard deviations are given as follows:

$\Delta\Gamma_\gamma = 5\%$	$\Delta D = 10\%$	
$\Delta S_0 = 10\ \%$	$\Delta S_1 = 17\%$	
$\Delta\Gamma_f(3^-) = 30\%$	$\Delta\Gamma_f(4^-) = 40\%$	for s-wave
$\Delta\Gamma_f(2^+) = 40\%$	$\Delta\Gamma_f(3^+) = 30\%$	for p-wave
$\Delta\Gamma_f(4^+) = 40\%$	$\Delta\Gamma_f(5^+) = 40\%$	for p-wave.

5.2 Covariances Based on Measurements

The GMA code was applied to estimated the covariances of the cross sections except the fission cross section.

1) Fission cross section

In JENDL-3.2, the fission cross section was obtained by the simultaneous evaluation[8] in the energy region above 30 keV. Figure 23 shows the standard deviation and correlation coefficient obtained.

2) Total cross section

In the energy region above 30 keV, the covariances were estimated from the following measurements:

Uttley et al.[121], Böckhoff et al.[122], Schwartz et al.[123], Green and Mitchell[124], Foster, Jr. and Glasgow[125], Poenitz et al.[126], and Poenitz and Whalen[127].

Figures 24 and 25 show the estimated standard deviations.

3) (n,2n) reaction cross section

There exist two sets of measurements: Frehaut et al.[128] and Mather et al.[129] The JENDL-3.2 evaluation is based on the measurements of Frehaut et al. Therefore, the covariances were estimated from the same experimental data. A systematic error of 6% was obtained from Ref. 128, and it was considered in the GMA analysis. In the energy region above 14 MeV, a relative standard deviation of 50% was assigned since no measurement is available. The result is shown in Fig. 26.

4) (n,3n) and (n,4n) reaction cross sections

There are two sets of measurements, i.e., Mather et al.[129] and Veeser and Arthur[130] for the (n,3n) reaction while there exists only one set of data measured by Vesser and Arthur[130] for the (n,4n) reaction. The JENDL-3.2 evaluation is based on the measurement of Vesser and Arthur, and the covariances were estimated from their data. A systematic error of 5%, which came from neutron flux, was taken into account in the GMA analysis.

5) (n,γ) reaction cross section

The covariances were estimated from the measurements of Corvi et al.[131], Gwin et al.[132], Kononov et al.[133], and Hopkins and Diven[134]. Error information for each experiment is given as follows:

Corvi et al.[131]

Statistical errors are given in the data. A systematic error of 4% due to normalization was considered in the GMA analysis.

Gwin et al.[132]

Statistical errors were calculated from those for fission and absorption cross sections. A systematic error of 15% was obtained from an uncertainty in the α values they measured.

Kononov et al.[133]

Total errors are given in the data. A systematic error of 10.3% was obtained from an uncertainty in the α values they measured.

Hopkins and Diven[134)]

Statistical errors are given in the data. A systematic error of 7% was obtained from the contribution of the ^{238}U contamination in the sample.

Relative standard deviations of more than 50% were assigned in the energy region above 10 MeV where the JENDL-3.2 evaluation is based on statistical model calculations, since the direct-capture process was not considered in the evaluation. Figure 27 shows the estimated standard deviation.

6) Average number of prompt neutrons

The covariances were estimated from eight sets of measurements[135-142)]. Error information for each experiment is given as follows:

Gwin et al.[135)] 500 keV – 10 MeV

Statistical errors are given in the data. A systematic error of 0.2% was obtained from Ref. 135.

Gwin et al.[136)] 0.005 eV – 60 eV

Total and statistical errors are given in the data. An average systematic error of 0.3% was calculated.

Gwin et al.[137)] 500 eV – 11.115 MeV

Statistical errors are given in the data. A systematic error of 0.3% was derived from Ref. 137.

Gwin et al.[138)] 50 eV – 7.2 MeV

Statistical errors are given in the data. A systematic error of 0.5% was assumed.

Frehaut et al.[139)] 1.143 MeV – 14.656 MeV

Statistical errors are given in the data. A systematic error of 0.3% was assumed.

Frehaut et al.[140)] 1.36 MeV – 28.280 MeV

Statistical errors are given in the data. A systematic error of 0.4% was assumed.

Frehaut and Boldeman[141)] 210 keV – 1.870 MeV

Statistical errors are given in the data. A systematic error of 0.5% was

assumed.

Howe[142] 17.0 MeV – 48.9 MeV

Total and statistical errors are given in the data. A systematic error of 1.9% was calculated.

Figure 28 shows the estimated standard deviation. In the whole energy region, the relative standard deviation is less than 1%.

7) Average number of delayed neutrons

The covariances were estimated from thirteen sets of measurements[143-155]. Error information for each experiment is given as follows:

Synetos et al.[143] 0.0253 eV

Total and statistical errors are given in the data. A systematic error of 4.5% was calculated.

Besant et al.[144] 0.63 MeV

Statistical errors are given in the data. A systematic error of 4.5% was assumed.

Cox[145] 0.96 MeV – 3.98 MeV

Total errors are given in the data. A systematic error of 5% was assumed.

Evans et al.[146] 0.05 MeV – 6.7 MeV

Total errors are given in the data. A systematic error of 5% was assumed.

Clifford et al.[147] 0.63 MeV

Total errors are given in the data. A systematic error of 5% was assumed.

Conant et al.[148] 0.0253 eV

Total errors are given in the data. A systematic error of 5% was assumed.

Masters et al.[149] 3.1, 14.9 MeV

Total errors are given in the data. A systematic error of 5% was assumed.

Keepin[150] 14.1, 14.9 MeV

Total errors are given in the data. A systematic error of 5% was assumed.

Maksyutenko et al.[151] 0.0253 eV, 2.4 MeV, 3.3 MeV

Total errors are given in the data. A systematic error of 5% was assumed.

Keepin et al.[152] 0.0253 eV, 1.45 MeV

Total errors are given in the data. A systematic error of 5% was assumed.

Rose et al.[153] 1 MeV

Total errors are given in the data. A systematic error of 5% was assumed.

Brunson et al.[154] 0.0253 eV, 0.29 MeV

Total errors are given in the data. A systematic error of 5% was assumed.

Snell et al.[155] 0.0253 eV

Total errors are given in the data. A systematic error of 5% was assumed.

Figure 29 shows the estimated standard deviation.

5.3 Covariances Based on Nuclear Model Calculations

The covariances of the inelastic scattering cross sections and the 1st order Legendre coefficient for the elastic scattering were obtained from statistical and optical model calculations on the KALMAN system. As for the Legendre coefficient, we used the experimental data on the total cross section mentioned in Sec. 5.2 to derive the covariances of the optical model parameters. On the other hand, the following measurements were used for the inelastic scattering:

Batchelor and Wyld[156], Drake[157], Knitter et al.[158], and Smith and Guenther[159].

Figure 30 shows the estimated standard deviation of the 1st order Legendre coefficient.

6. Uranium-238

Covariances were obtained for the total, inelastic scattering, (n,2n), (n,3n), (n,γ), and fission cross sections, resolved and unresolved resonance parameters, and the 1st order Legendre coefficient for the elastic angular distribution.

6.1 Covariances of Resonance Parameters

In JENDL-3.2, resolved resonance parameters are given below 10 keV with the multi-level Breit-Wigner formula. The standard deviations of the parameters are based on the values obtained by Olsen et al.[160,161] and Moxon et al.[162]

Unresolved resonance parameters are given in the energy region from 10 keV to 150 keV. Uncertainties in an average level spacing D, neutron strength functions S_0, S_1, S_2, and an average capture width Γ_γ were deduced from the energy dependence of these parameters calculated with the ASREP code:

$\Delta D = 5\%$ $\Delta\Gamma_\gamma = 1.5\%$

$\Delta S_0 = 13\%$, $\Delta S_1 = 18\%$ $\Delta S_2 = 20\%$.

6.2 Covariances Based on Measurements

1) Total cross section

The GMA code was applied to estimate the covariances from the following measurements:

Whalen and Smith[163]

Statistical errors are given in the data. A systematic error of 3% was assumed.

Poenitz et al.[126]

Total and statistical errors are given in the data. A systematic error of 0.4 was deduced.

Tsubone et al.[164]

Total errors are given in the data. A systematic error of 2.2% was deduced.

Foster, Jr. and Glasgow[125]

Total errors are given in the data. A systematic error of 0.5% was deduced.

Bratenahal et al.[165]

Total errors are given in the data. A systematic error of 0.5% is given in Ref. 165.

Peterson et al.[166]

Total errors are given in the data. A systematic error of 0.5% is given in Ref. 166.

Figure 31 shows the estimated standard deviations.

2) (n,2n) and (n,3n) reaction cross sections

In JENDL-3.2, the (n,2n) reaction cross section was evaluated from the measurements of Veeser and Arthur[130], Frehaut et al.[128], and Karius et al.[167] The covariances of the cross section were obtained from these data by using the spline-function fitting. Error information for each data set is given as follows:

Vesser and Arthur[130]

Total errors are given in the data. A systematic error of 3.5% was assumed.

Frehaut et al.[128]

Total errors are given in the data. A systematic error of 3.5% was assumed.

Karius et al.[167]

Partial errors are given in the data.

The (n,3n) reaction cross section in JENDL-3.2 is based on the measurements of Veeser and Arthur[130] The covariances of the cross section was obtained in the same manner as the (n,2n) reaction.

Figures 32 and 33 shows the standard deviations of the (n,2n) and (n,3n) cross sections, respectively.

3) Fission cross section

The covariances were obtained from the simultaneous evaluation[8], and the result is shown in Fig. 34.

6.3 Covariances Based on Nuclear Model Calculations

1) Inelastic scattering cross sections

In JENDL-3.2, the cross sections are given for 33 excited levels, among which the 28th to 33rd levels were created so as to reproduce available experimental data on neutron emission spectra. The covariances of the cross sections for the real 27 levels were obtained from the coupled-channel and statistical model calculations on the KALMAN system. The uncertainties in the model parameters were derived from the measurements[168-173] for the 1st and 2nd excited states. A standard deviation of 20% was assumed for the six pseudo levels and the continuum level.

2) (n,γ) reaction cross section

The CASTHY code was used to estimate the covariances in the energy region from 150 keV to 2 MeV. The uncertainties in the model parameters were derived by fitting to the following experimental data:

Fricke[174], Drake et al.[175], Lindner[176], Poenitz[177], Diven et al.[178], McDaniels et al.[179], Barry et al.[180], Perkin et al.[181], Broda[182], Huang et al.[183], Panitkin et al.[184], Davletshin et al.[185], Buleeva et al.[186], and Kazakov et al.[187]

Above 2 MeV, the direct-semidirect model[188] was used to estimate the covariances and the result was combined with those obtained by the CASHY calculations. Figure 35 shows the estimated standard deviation.

3) Angular distributions for the elastic scattering

The covariances of the 1st order Legendre coefficient for the elastic scattering

was obtained by using the ECIS code on the KALMAN system. The uncertainties in the optical model parameters were estimated by fitting to the measurements on the total cross section mentioned in Sect. 6.2. Figure 36 shows the estimated standard deviation.

7. Plutonium-239

Covariances were obtained for the total, inelastic scattering, (n,2n), (n,3n), (n,4n), (n,γ), and fission cross sections, resolved and unresolved resonance parameters, and the 1st order Legendre coefficient for the elastic angular distribution.

7.1 Covariances of Resonance Parameters

In JENDL-3.2, resolved resonance parameters are given below 2.5 keV with the Reich-Moore formula. The covariances of the parameters were obtained from the analysis of Derrien[189] in the energy region from 1 keV to 2.5 keV. No covariance was given below 1 keV since the data were no longer available at ORNL where the evaluation of the parameters had been performed.

The covariances of the unresolved resonance parameters which are given in the range of 2.5 keV to 30 keV was taken from the previous work[93]:

$\Delta D = 5\%$, $\Delta\Gamma_\gamma = 1\%$

$\Delta S_0 = 10\%$ $\Delta S_1 = 15\%$

$\Delta\Gamma_f(0^+, 1^+) = 15\%$ $\Delta\Gamma_f(0^-, 1^-, 2^-) = 20\%$,

where the meaning of the symbols is the same as that in Sect. 6.1.

7.2 Covariances Based on Measurements

1) Total cross section

In the energy region from 30 keV to 7 MeV, the covariances were estimated on the basis of the optical model calculations, which are described in Sect. 7.3. Above 7 MeV, the GMA code was used to obtain the covariances from the following measurements:

Schwartz et al.[123]

Statistical error is given in the data. A systematic error of 1.1% was deduced.

Foster, Jr. and Glasgow[125]

Total errors are given in the data. A systematic error of 0.5% was deduced.

Nadolny et al.[190]

Statistical errors are given in the data. A systematic error of 1% was deduced.

Poenitz and Whalen[127]

Total errors are given in data. A systematic error of 0.93% was deduced.

The estimated standard deviation is shown in Fig. 37.

2) (n,2n) reaction cross section

The GMA code was applied to estimate the covariances of the cross section from the measurements of Frehaut et al.[191] A systematic error of 9%, which was deduced in Ref. 191, was put into the code. The result is shown in Fig. 38.

3) (n,3n) and (n,4n) reaction cross sections

The JENDL-3.2 evaluation is based on nuclear model calculations. However, the parameters required as input to the model code are no longer available. Moreover, experimental data on these reactions are very scarce, and it is impossible to determine the covariances experimentally. Therefore, we used the rule of Oh[13], which was applied to the $^{16}O(n,np)$ and $^{16}O(n,n\alpha)$ reactions, with a full correlation.

4) (n,γ) reaction cross section

The GMA code was used to estimated the covariances in the energy region from 30 keV to 1 MeV. The measurements used are given as follows:

Spivak et al.[192], Hopkins and Diven[134], and Kononov et al.[193]

The variance obtained at 1 MeV was used without any correlation up to 8 MeV. In the energy region above 8 MeV, a relative standard deviation of 100% was assumed since the direct capture was not considered in the JENDL-3.2 evaluation. Figure 39 shows the estimated standard deviations.

5) Fission cross section

The covariances of the fission cross section was obtained by the simultaneous evaluation[8], and the result is shown in Fig. 40.

7.3 Covariances Based on Nuclear Model Calculations

1) Total cross section

The optical model code ELIESE-3 was used to estimate the covariances in the energy region from 30 keV to 7 MeV. The uncertainties in the optical model parameters were obtained by fitting to the total cross section data mentioned in Sect. 7.2 and to the measurements of Poenitz et al.[126] Figure 41 shows the estimated result.

2) Inelastic scattering cross section

The CASTHY code yielded the covariances the cross sections. The uncertainties in the model parameters were obtained by fitting to the measurements of Haouat et al.[170] For the 1st to 5th, 7th, and 9th levels, a standard deviation of 20% was assumed with a full correlation in the energy region above 4 MeV, since the cross sections for these levels were evaluated with the coupled-channel model in JENDL-3.2 and thus a strong correlation was expected.

3) Angular distributions for the elastic scattering

The ECIS code was used to estimate the covariances of the 1st order Legendre coefficient. Figure 42 shows the estimated standard deviation.

8. Concluding Remarks

Covariances of nuclear data were estimated for ^{16}O, ^{23}Na, Fe, ^{235}U, ^{238}U, and ^{239}Pu contained in JENDL-3.2. The quantities of which covariances were obtained are cross sections, resolved and unresolved resonance parameters, and the 1st order Legendre coefficient for the elastic scattering. The uncertainty in the Legendre coefficient was estimated in order to calculate an uncertainty in an average cosine of elastic-scattering angles. As for ^{235}U, we obtained the covariances of the average number of prompt and delayed neutrons emitted in fission.

In covariance estimation, we used the same methodology that had been taken in the JENDL-3.2 evaluation in order to keep a consistency between mean values and their covariances. The covariances of fission cross sections were taken from the simultaneous evaluation which had been performed in the JENDL-3.2 evaluation.

The results obtained were compiled in the ENDF-6 format, and will be put into the JENDL-3.2 Covariance File which is one of the JENDL special purpose files managed by the JAERI Nuclear Data Center. The data are also used in making the

integrated group cross-section library promoted by the PNC.

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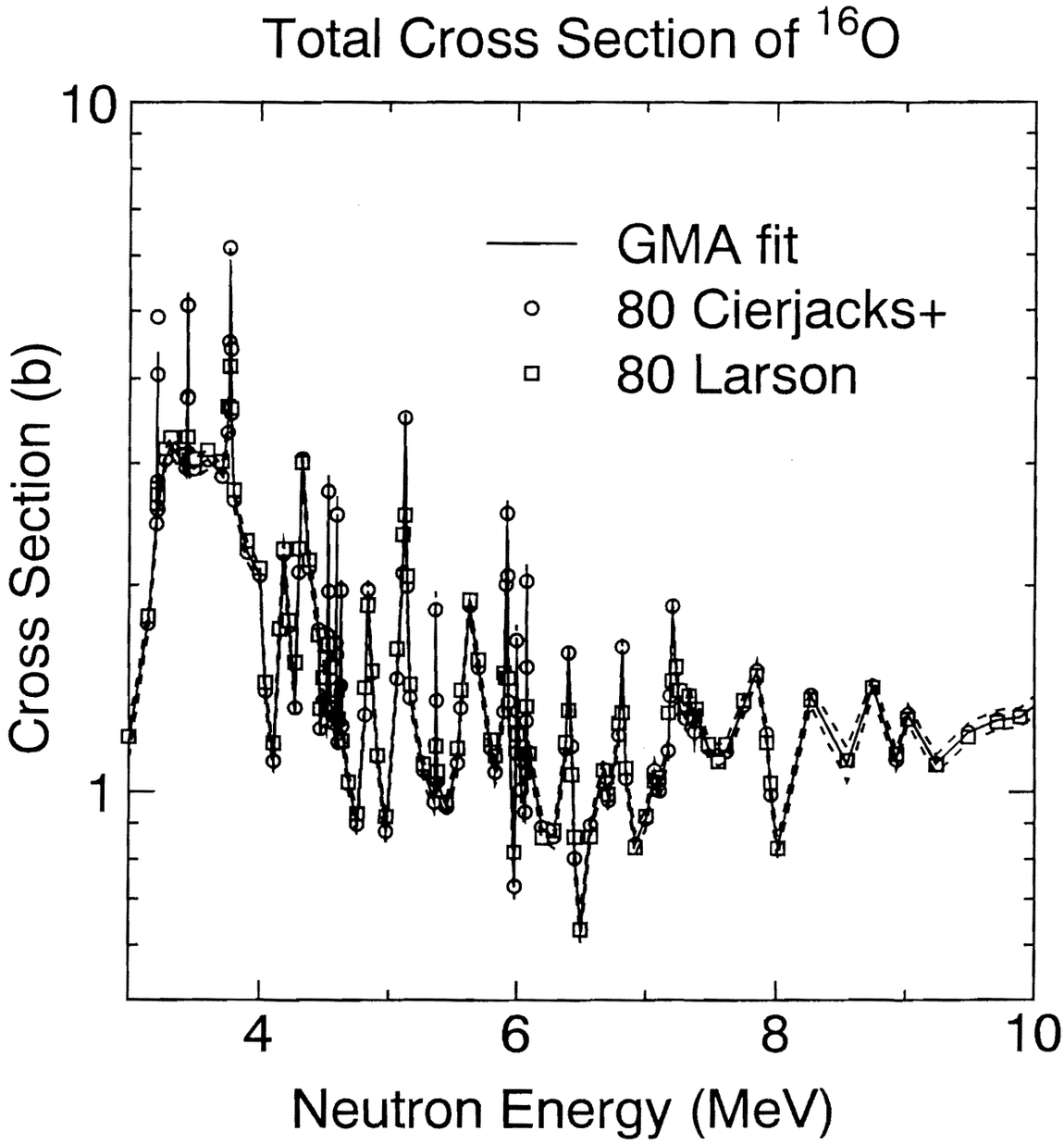

Fig. 1 Total cross section of ^{16}O below 10 MeV.
The solid line stands for the best estimate, and the dashed ones standard deviations.

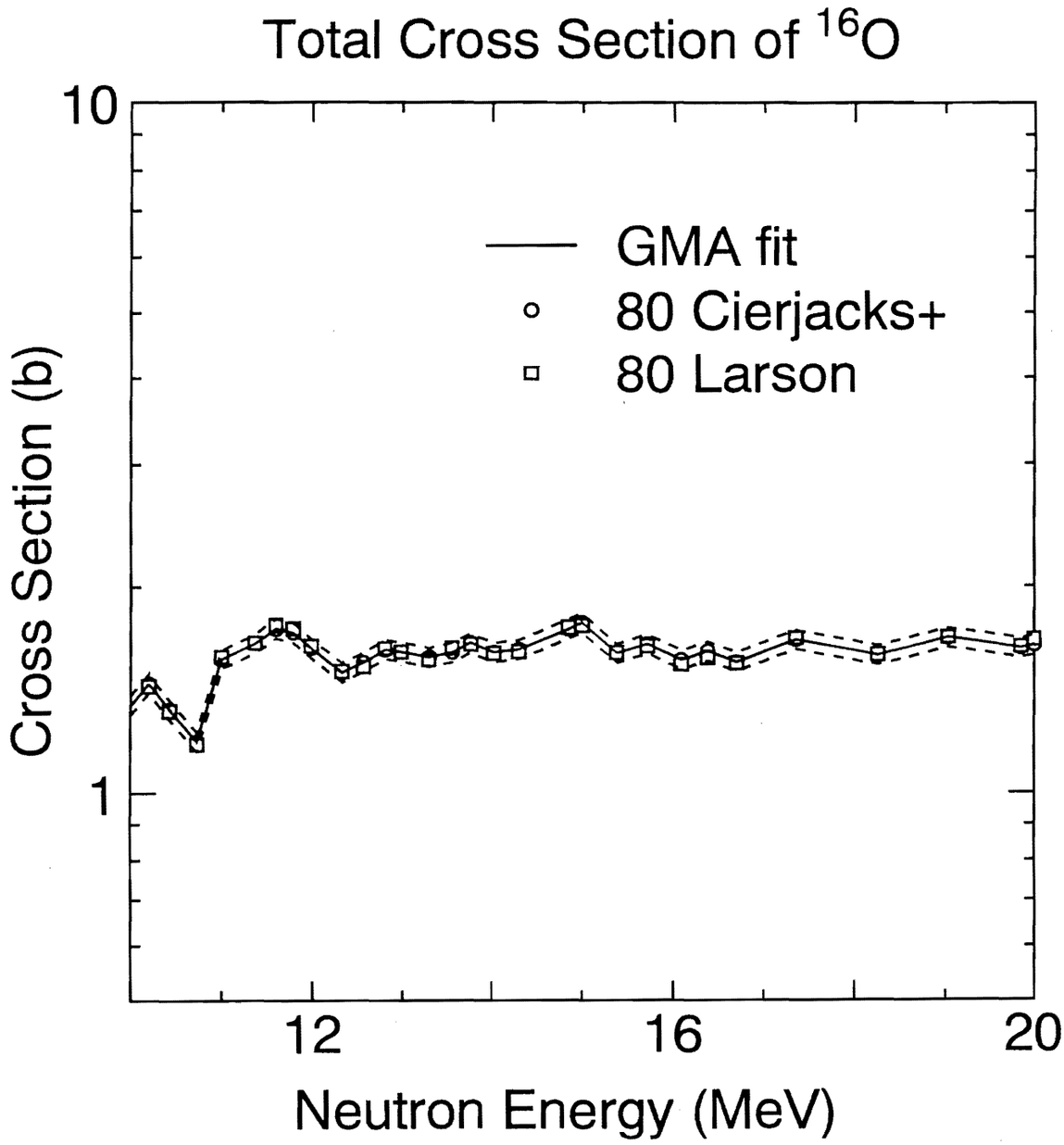

Fig. 2 Total cross section of ^{16}O above 10 MeV.
The solid line stands for the best estimate, and the dashed ones standard deviations.

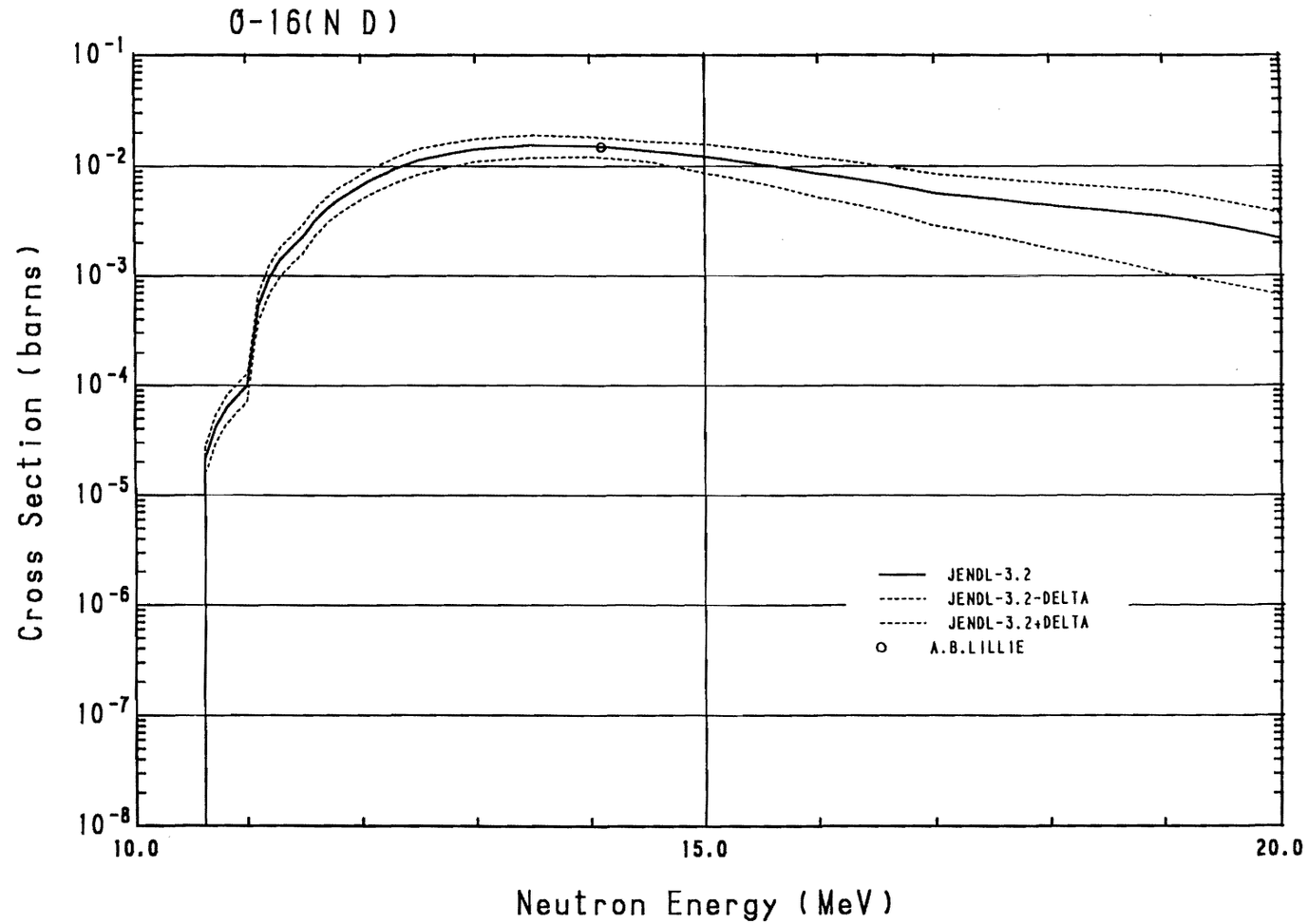

Fig. 3 (n,d) reaction cross section of ^{16}O.
The solid line stands for the JENDL-3.2 curve, and the dashed ones its standard deviations.

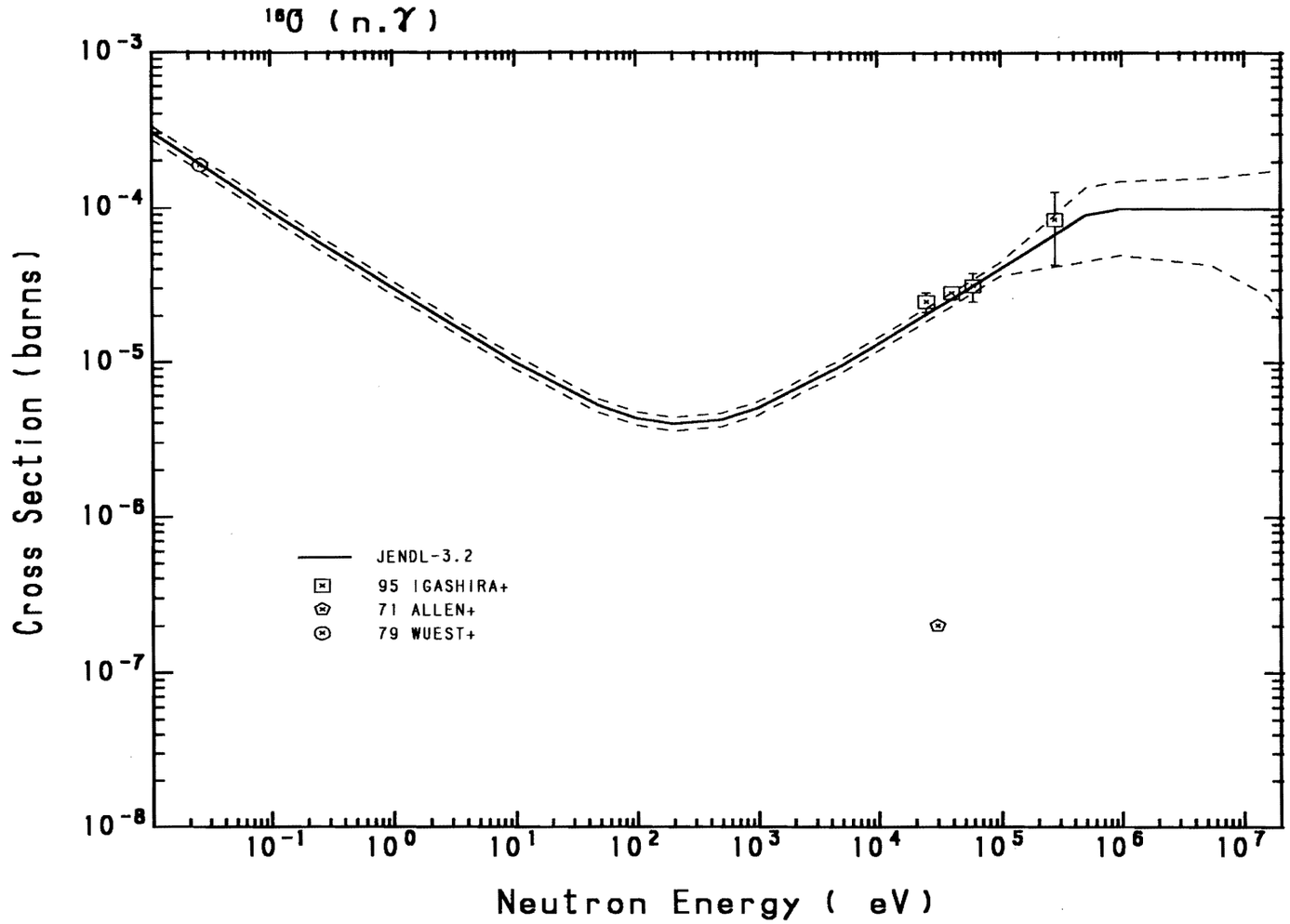

Fig. 4 (n,γ) reaction cross section of ^{16}O.
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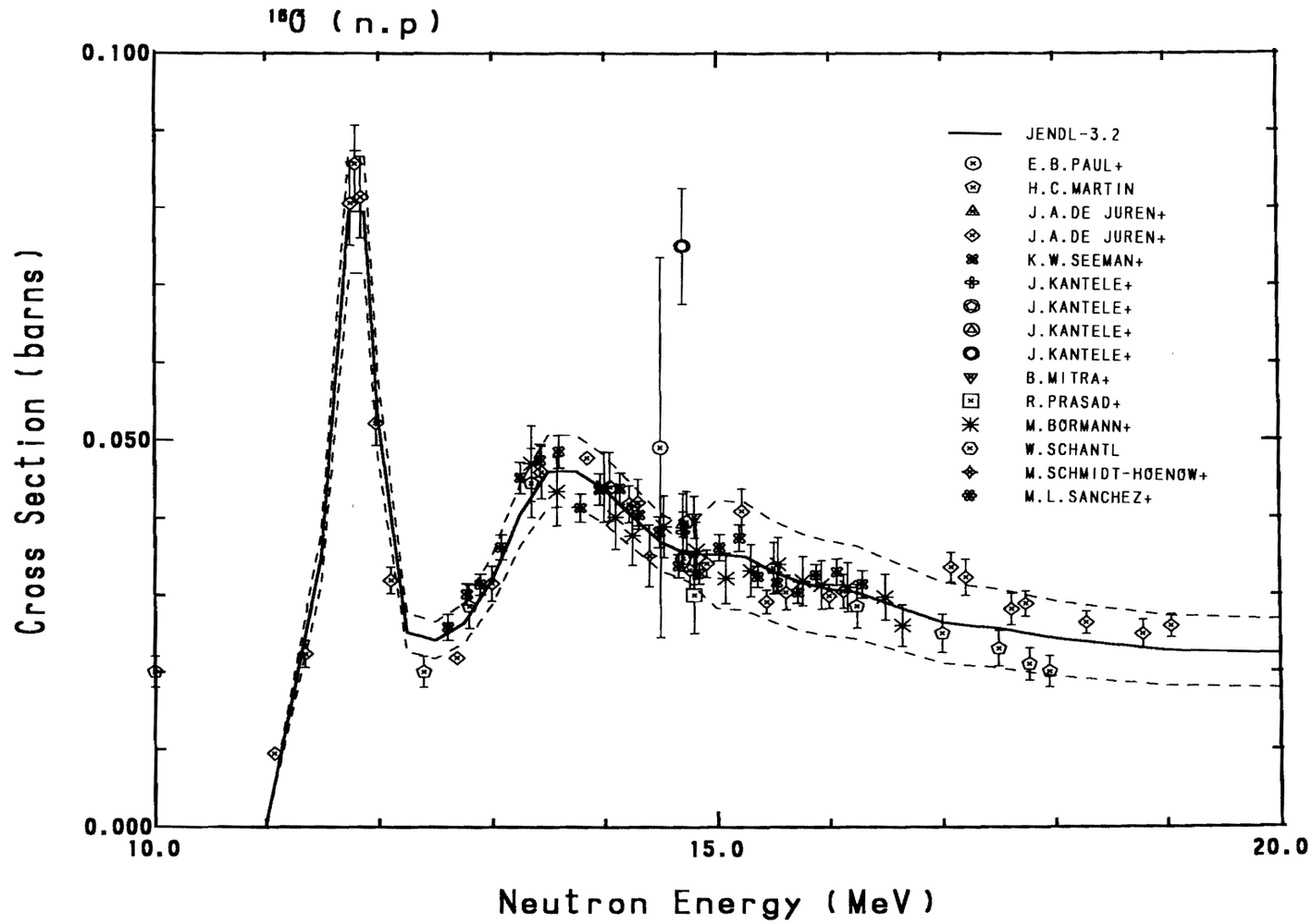

Fig. 5 (n,p) reaction cross section of ^{16}O.
The solid line stands for the JENDL-3.2 curve, and the dashed ones its standard deviations.

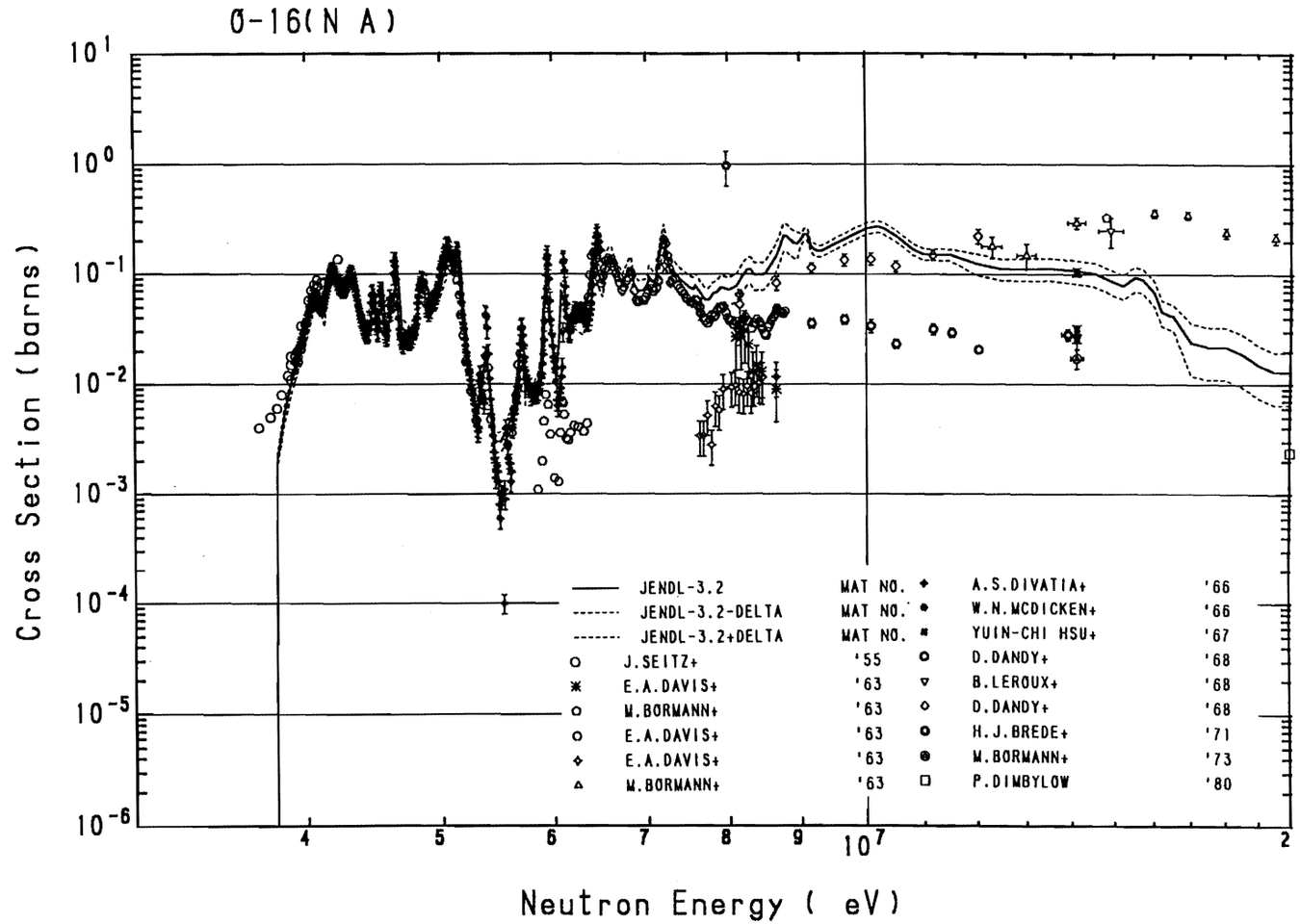

Fig. 6 (n,α) reaction cross section of ^{16}O.
The solid line stands for the JENDL-3.2 curve, and the dashed ones its standard deviations.

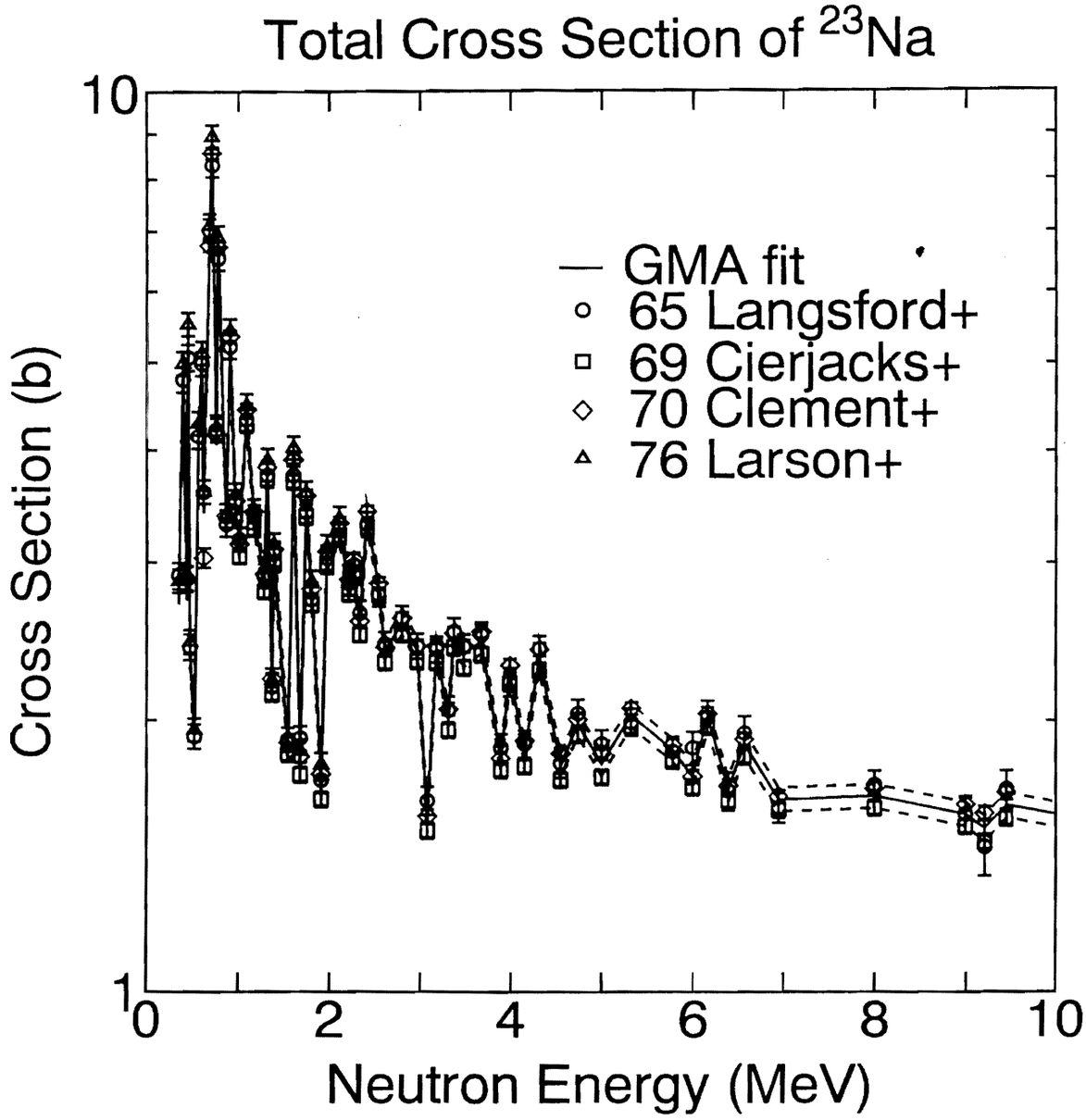

Fig. 7 Total cross section of ^{23}Na below 10 MeV.
The solid line stands for the best estimate, and the dashed ones standard deviations.

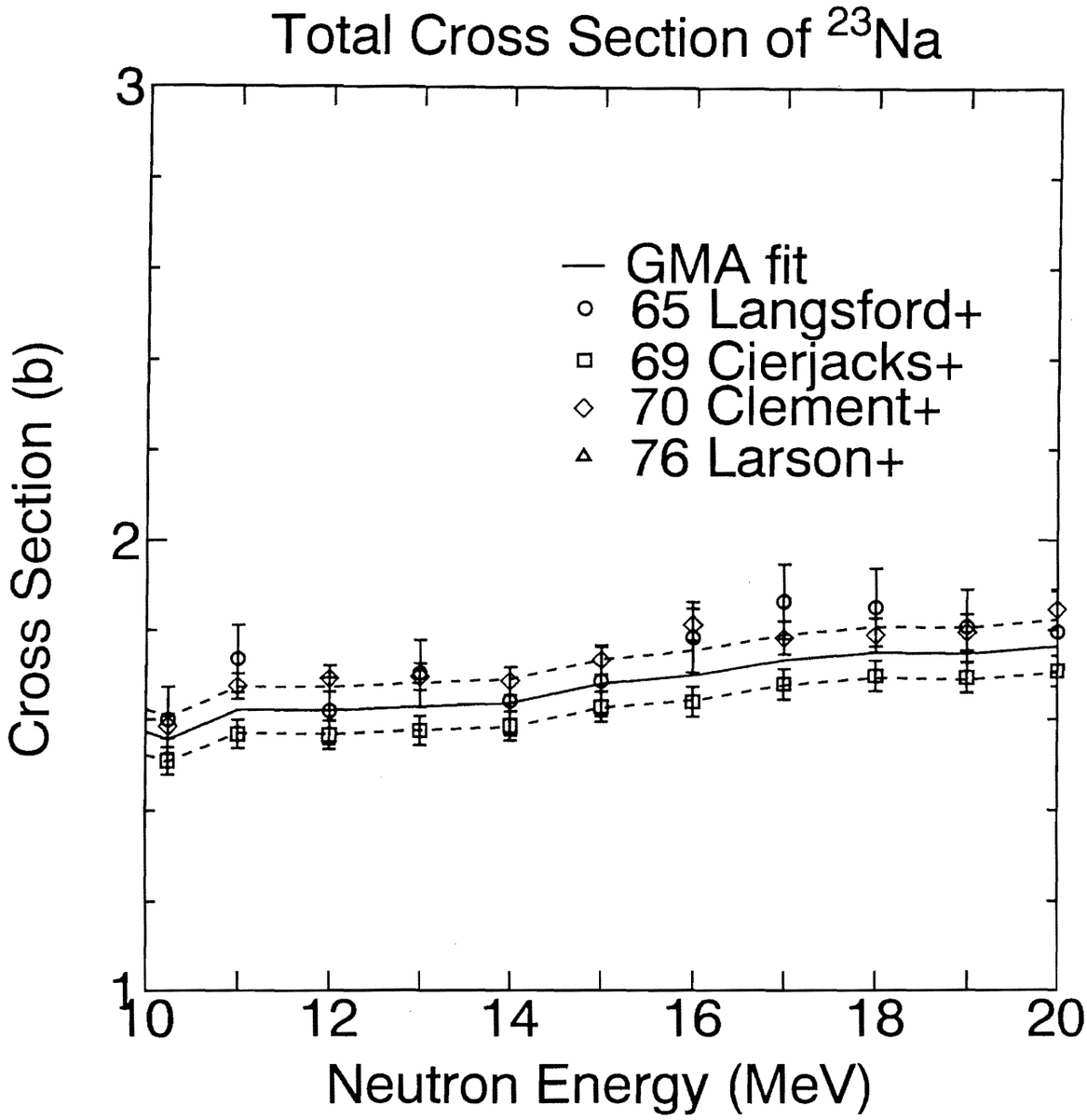

Fig. 8 Total cross section of ^{23}Na above 10 MeV.
The solid line stands for the best estimate, and the dashed ones standard deviations.

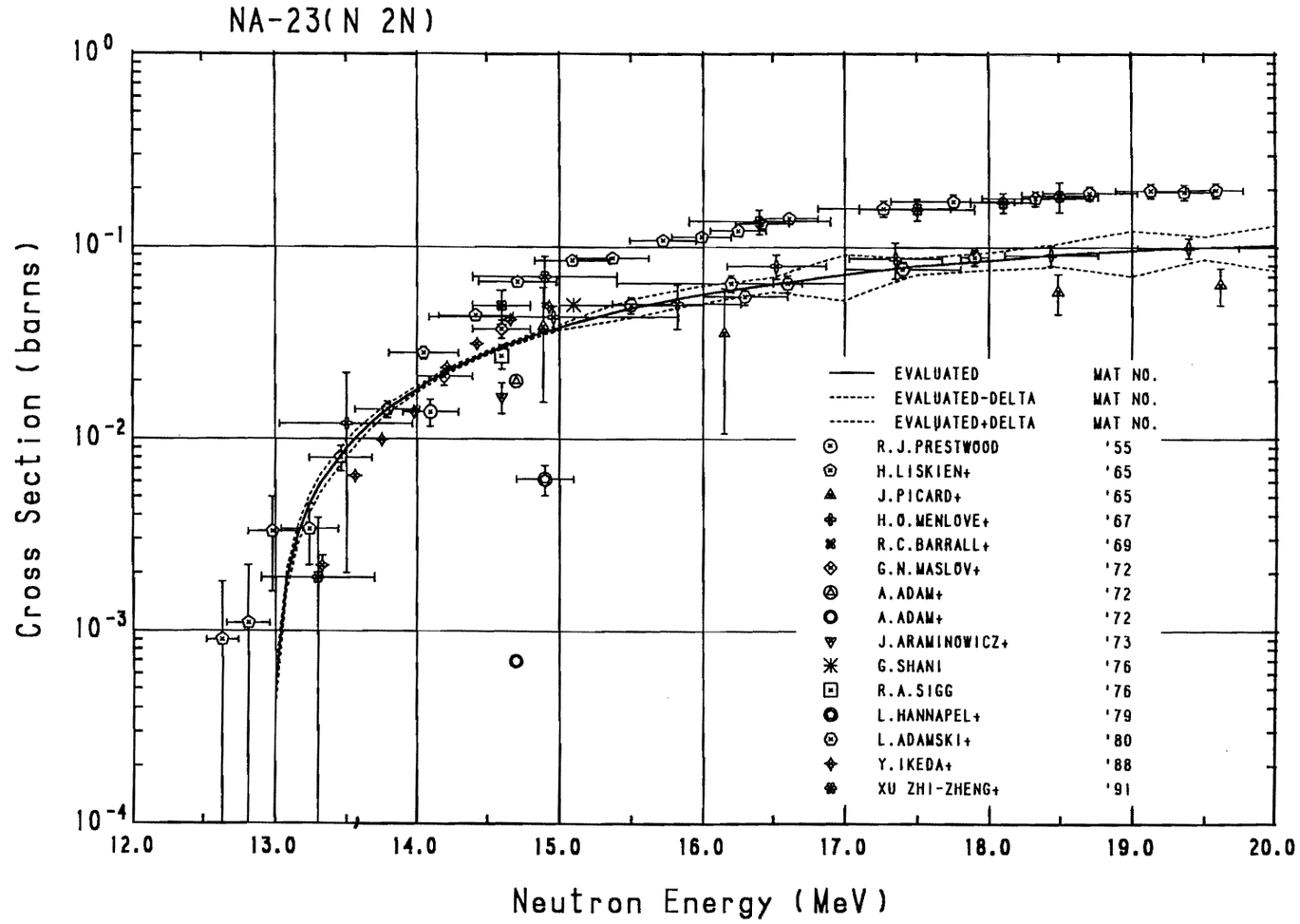

Fig. 9 (n,2n) cross section of ^{23}Na.
The solid line stands for the JENDL-3.2 curve, and the dashed ones its standard deviations.

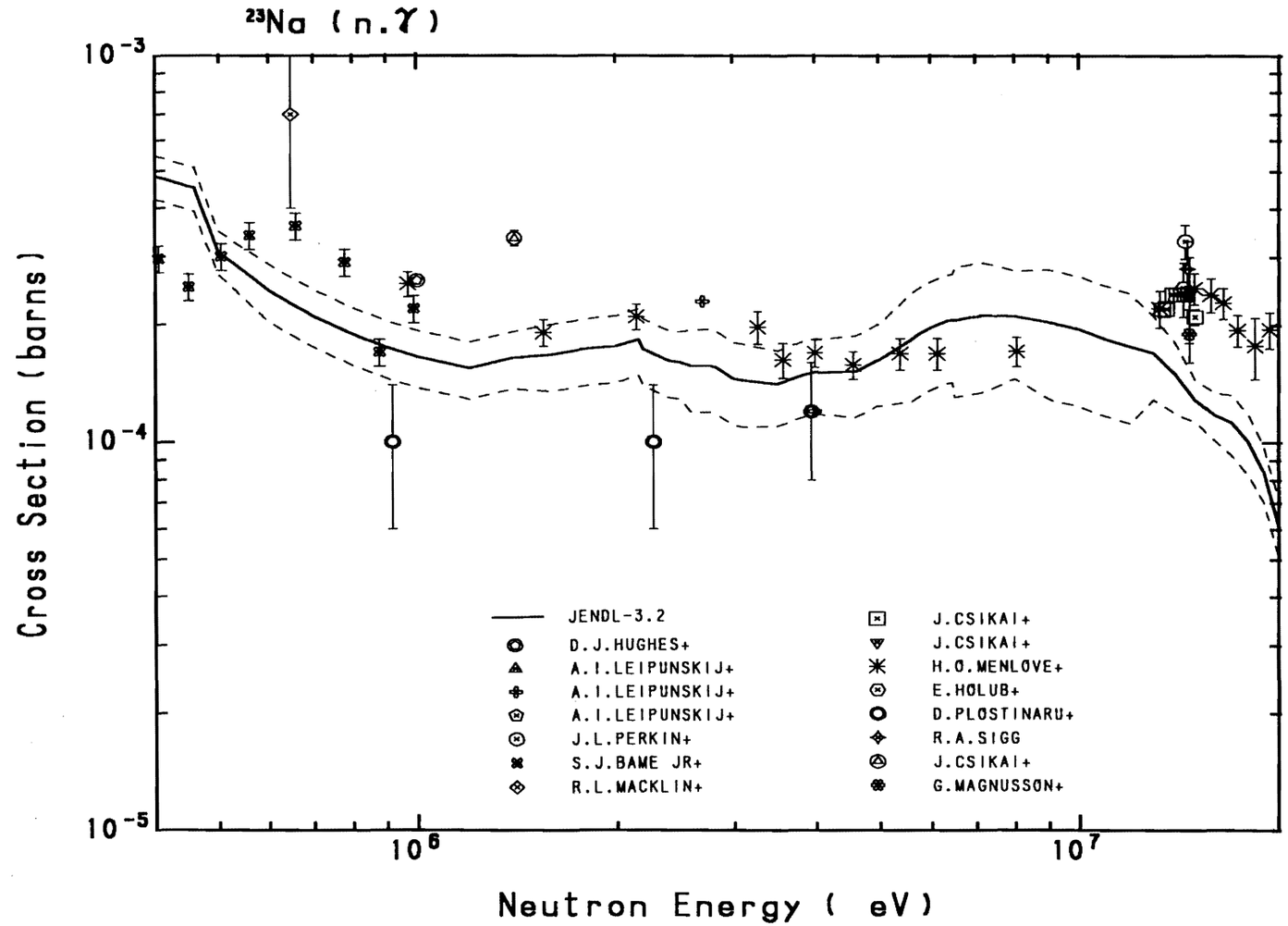

Fig. 10 (n,γ) reaction cross section of ^{23}Na.
The solid line stands for the JENDL-3.2 curve, and the dashed ones its standard deviations.

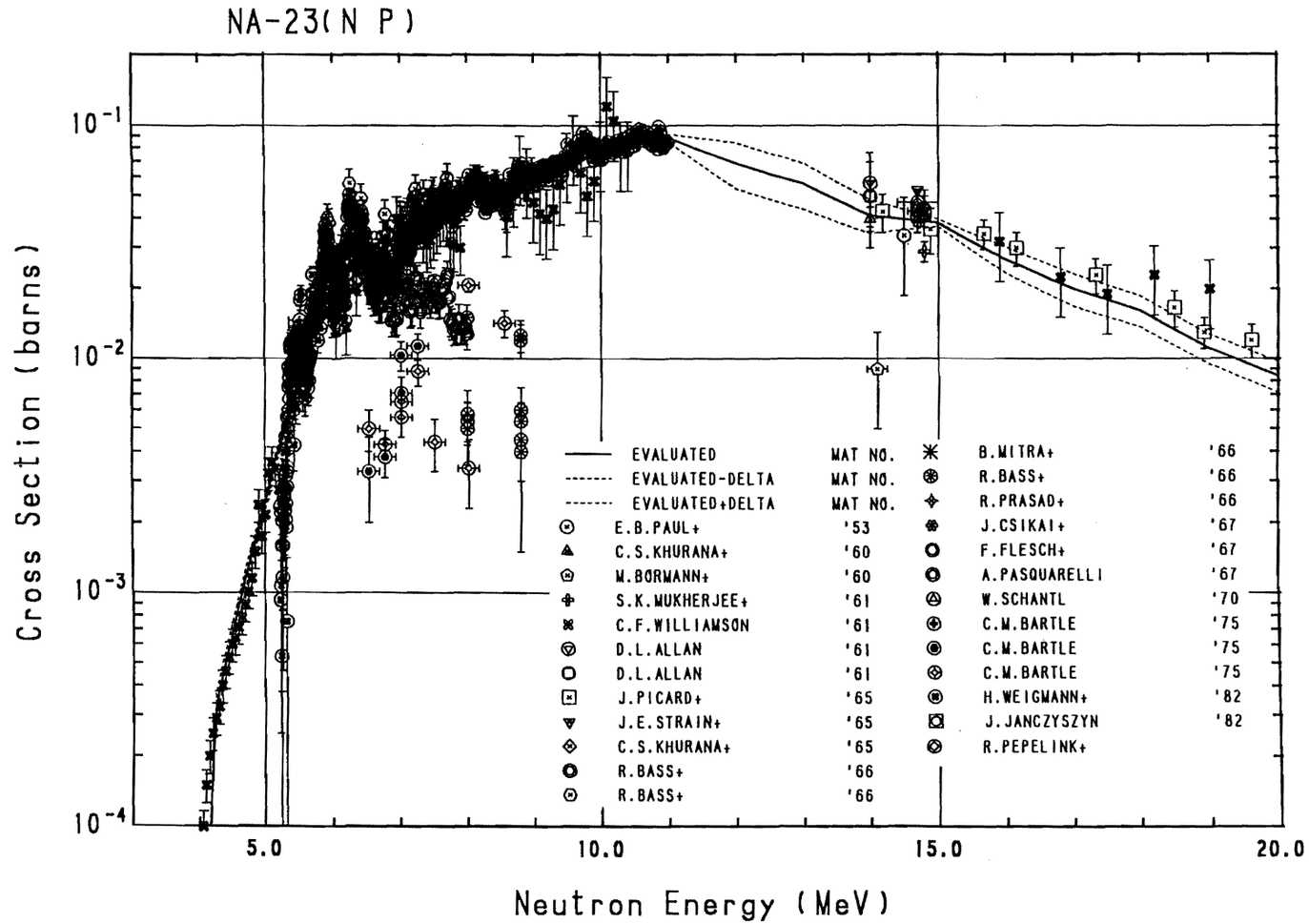

Fig. 11 (n,p) reaction cross section of ^{23}Na.
The solid line stands for the JENDL-3.2 curve, and the dashed ones its standard deviations.

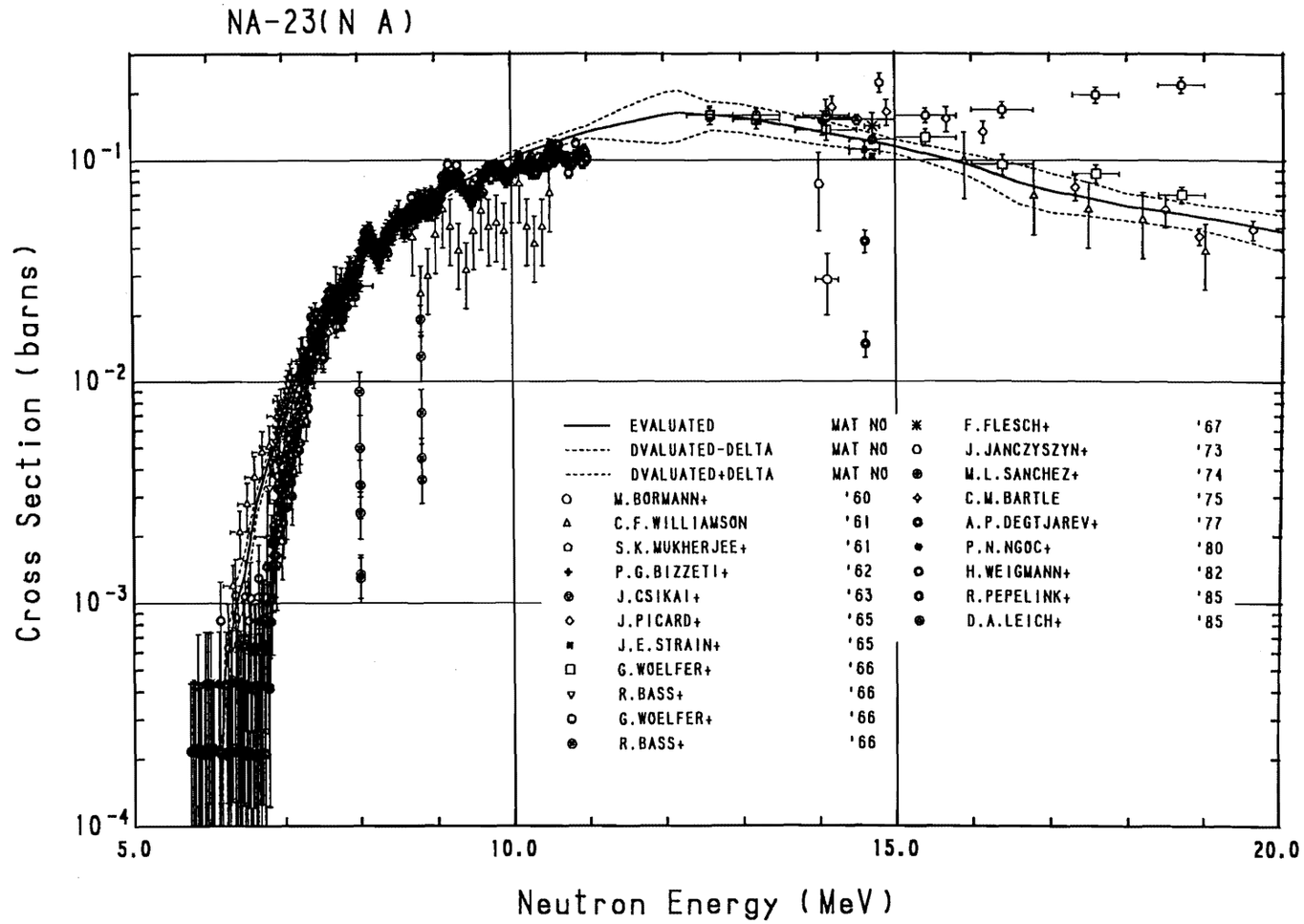

Fig. 12 (n,α) reaction cross section of ^{23}Na.
The solid line stands for the JENDL-3.2 curve, and the dashed ones its standard deviations.

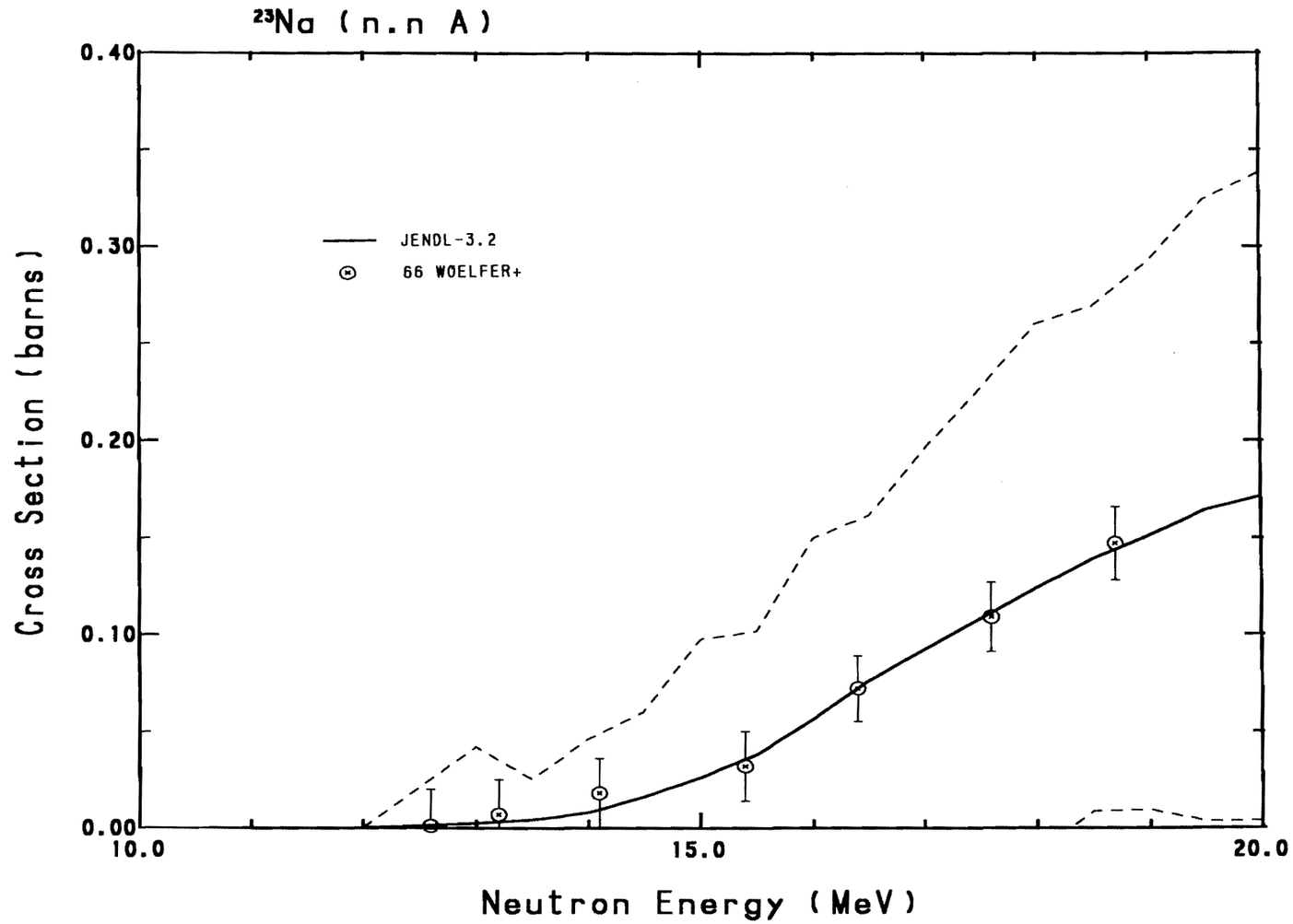

Fig. 13 (n,nα) reaction cross section of ^{23}Na.
The solid line stands for the JENDL-3.2 curve, and the dashed ones its standard deviations.

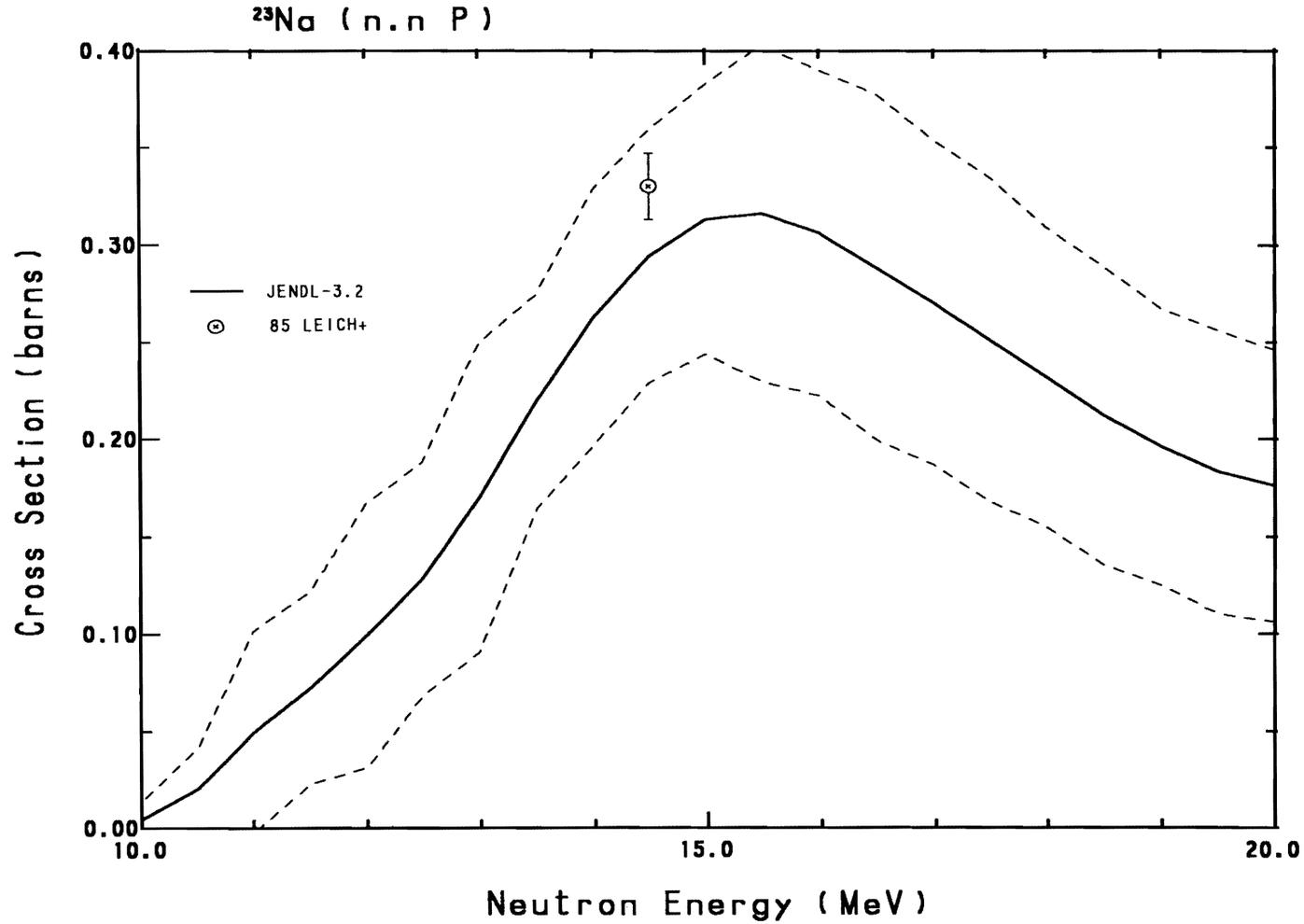

Fig. 14 (n,np) reaction cross section of ^{23}Na.
The solid line stands for the JENDL-3.2 curve, and the dashed ones its standard deviations.

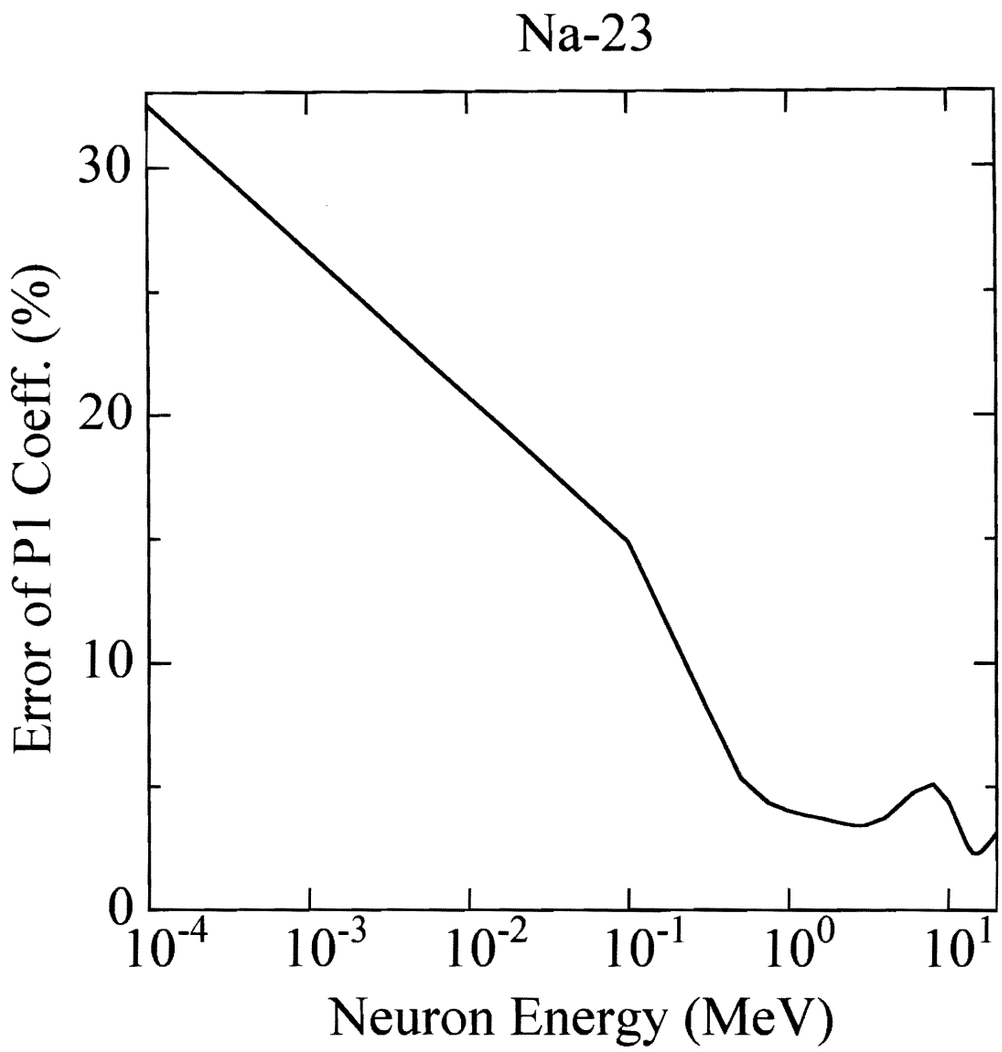

Fig. 15 Error of the 1st order Legendre-polynomial coefficient for ^{23}Na.

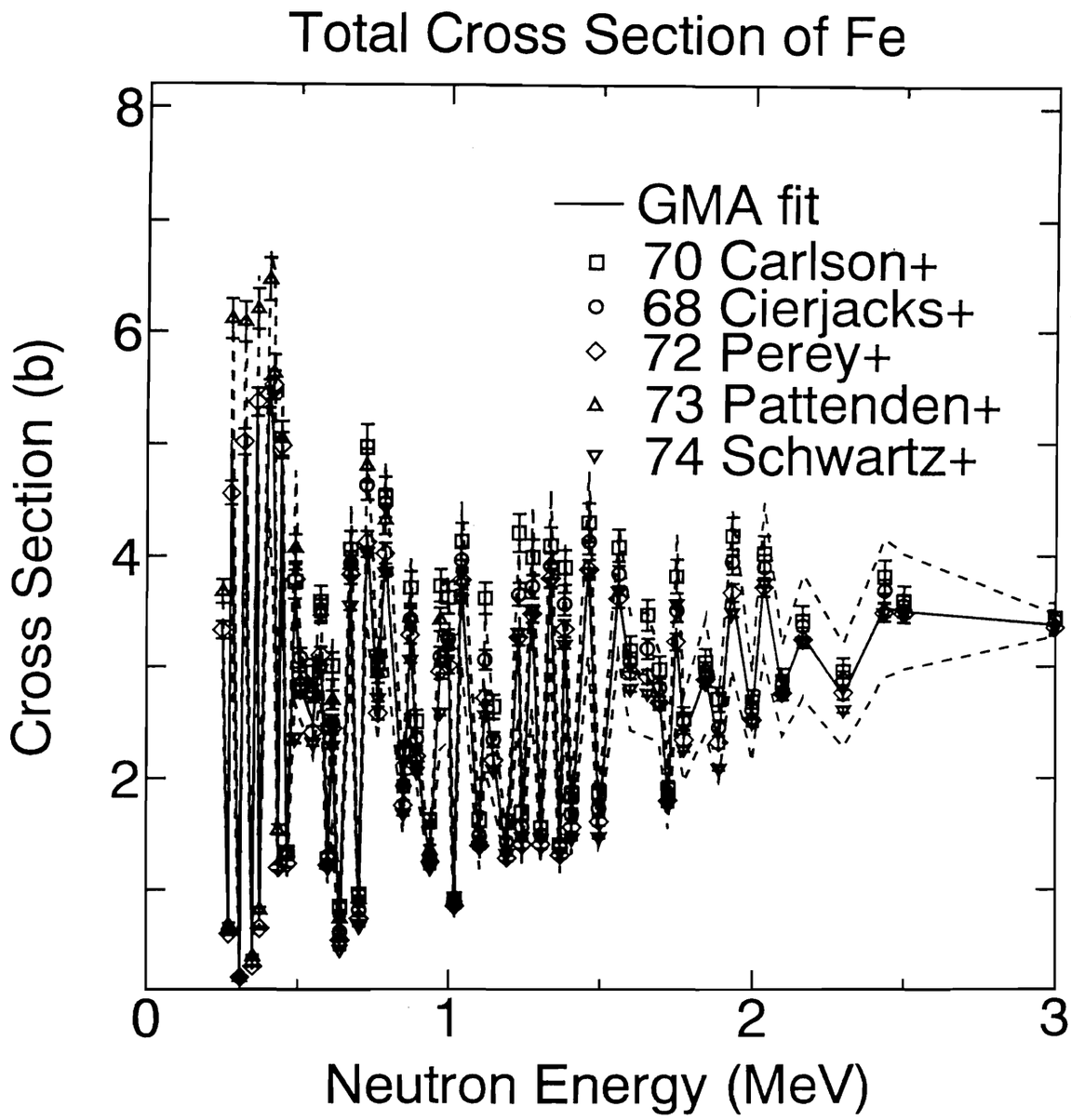

Fig. 16 Total cross section of natural iron below 3 MeV.
The solid line stands for the best estimate, and the dashed ones standard deviations.

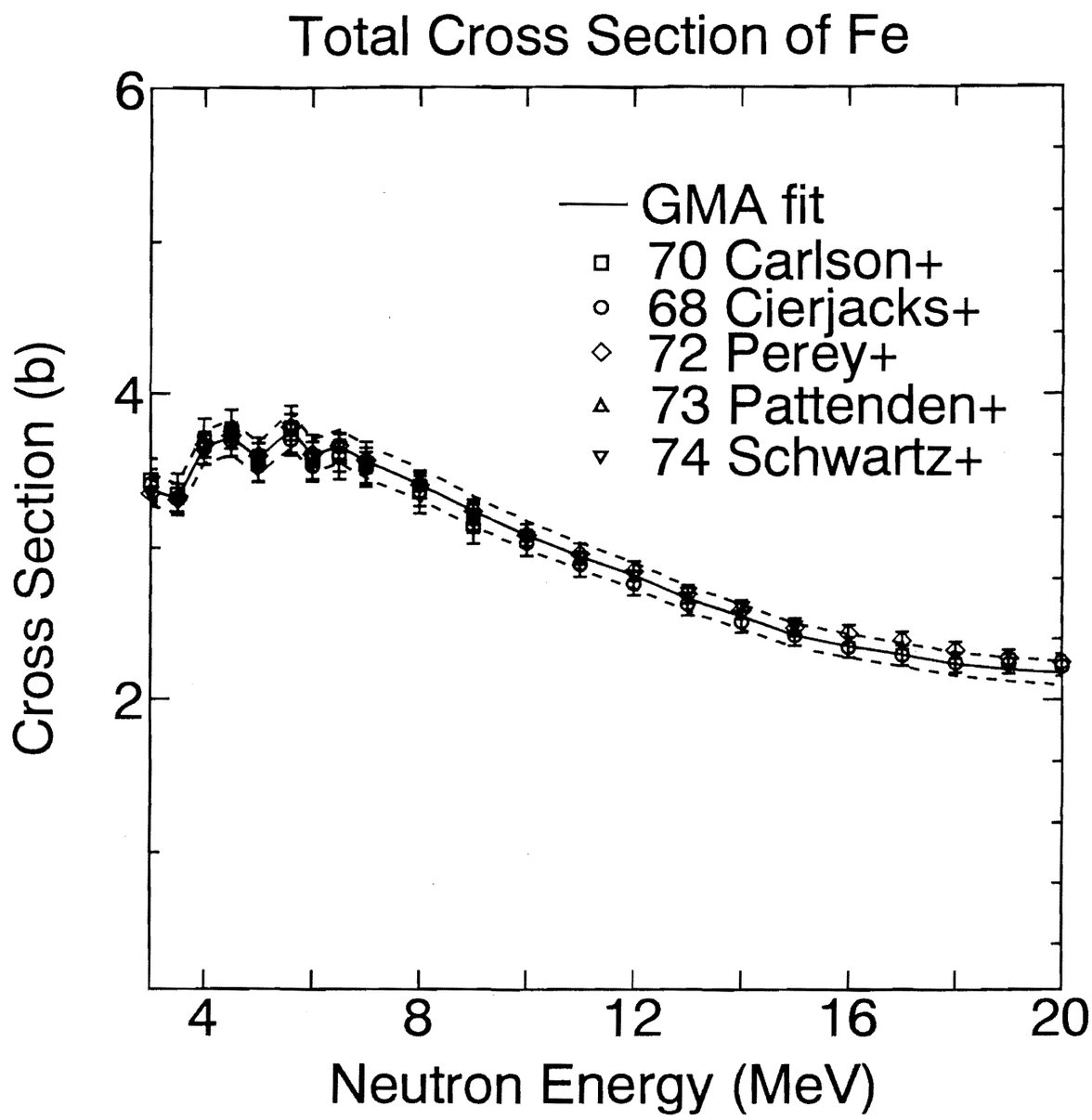

Fig. 17 Total cross section of natural iron above 3 MeV.
The solid line stands for the best estimate, and the dashed ones standard deviations.

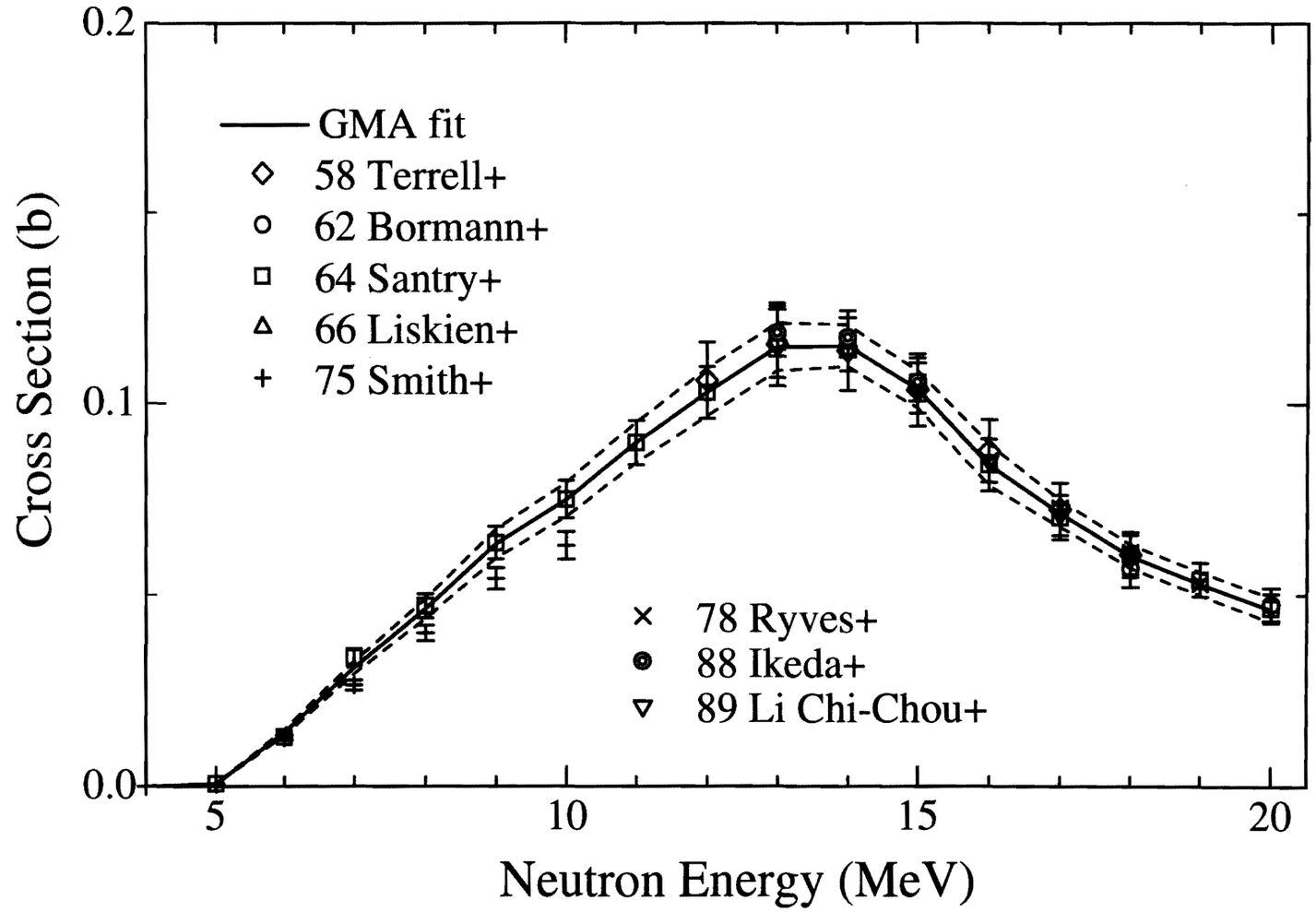

Fig. 18 (n,p) reaction cross section of ^{56}Fe.
The solid line stands for the best estimate, and the dashed ones standard deviations.

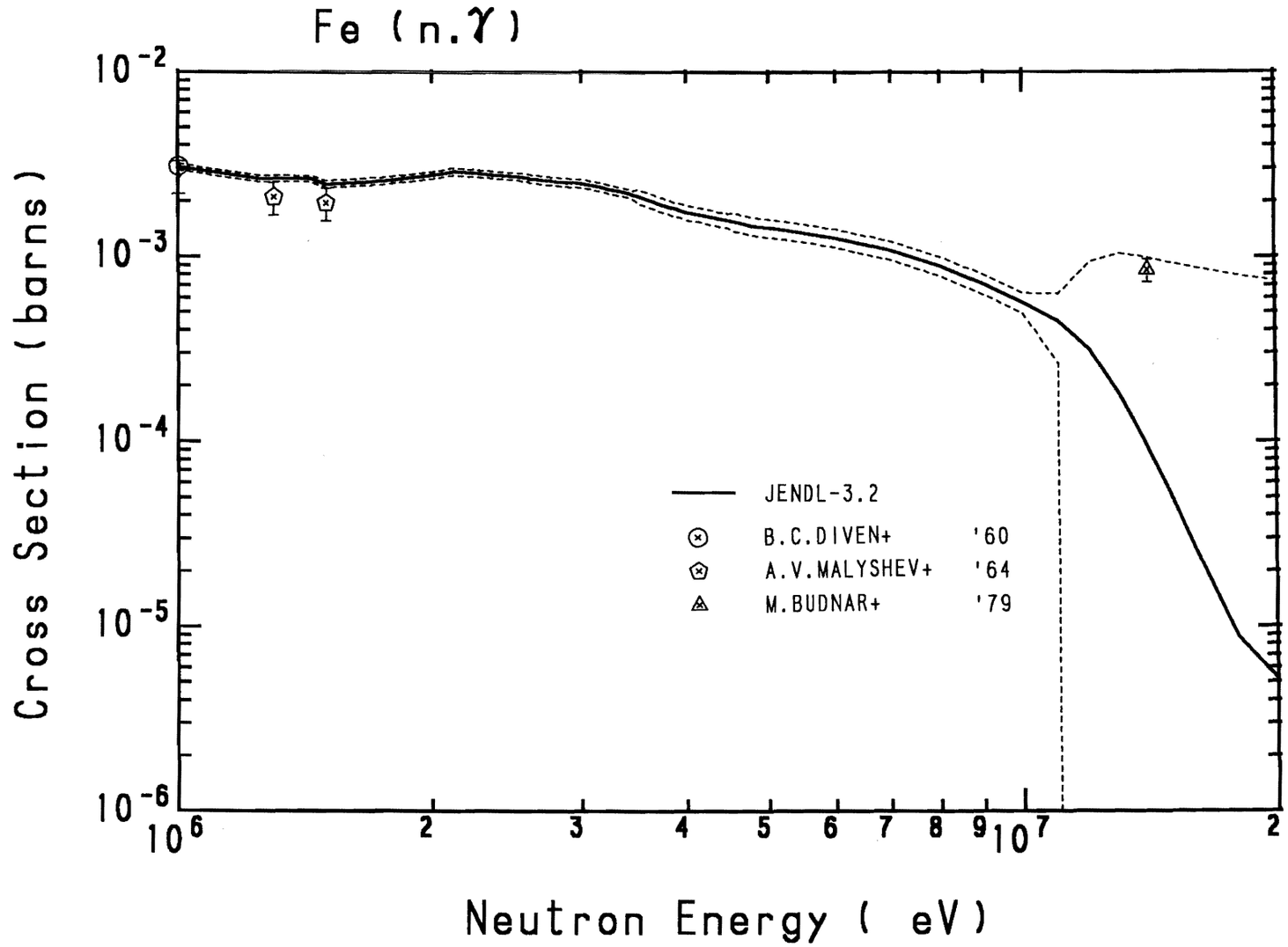

Fig. 19 (n,γ) reaction cross section of natural iron.
The solid line stands for the JENDL-3.2 curve, and the dashed ones its standard deviations.

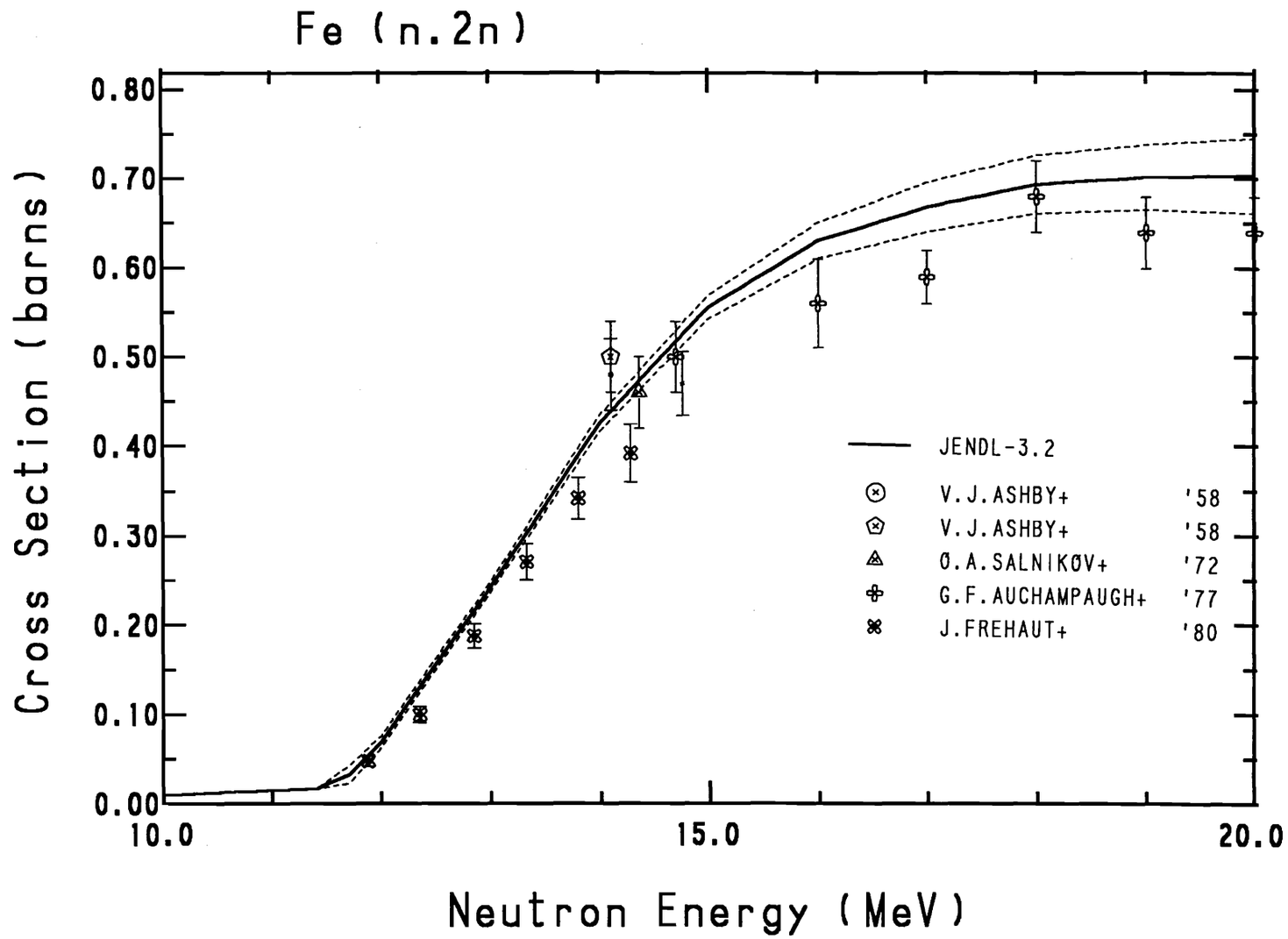

Fig. 20 (n,2n) reaction cross section of natural iron.
The solid line stands for the JENDL-3.2 curve, and the dashed ones its standard deviations.

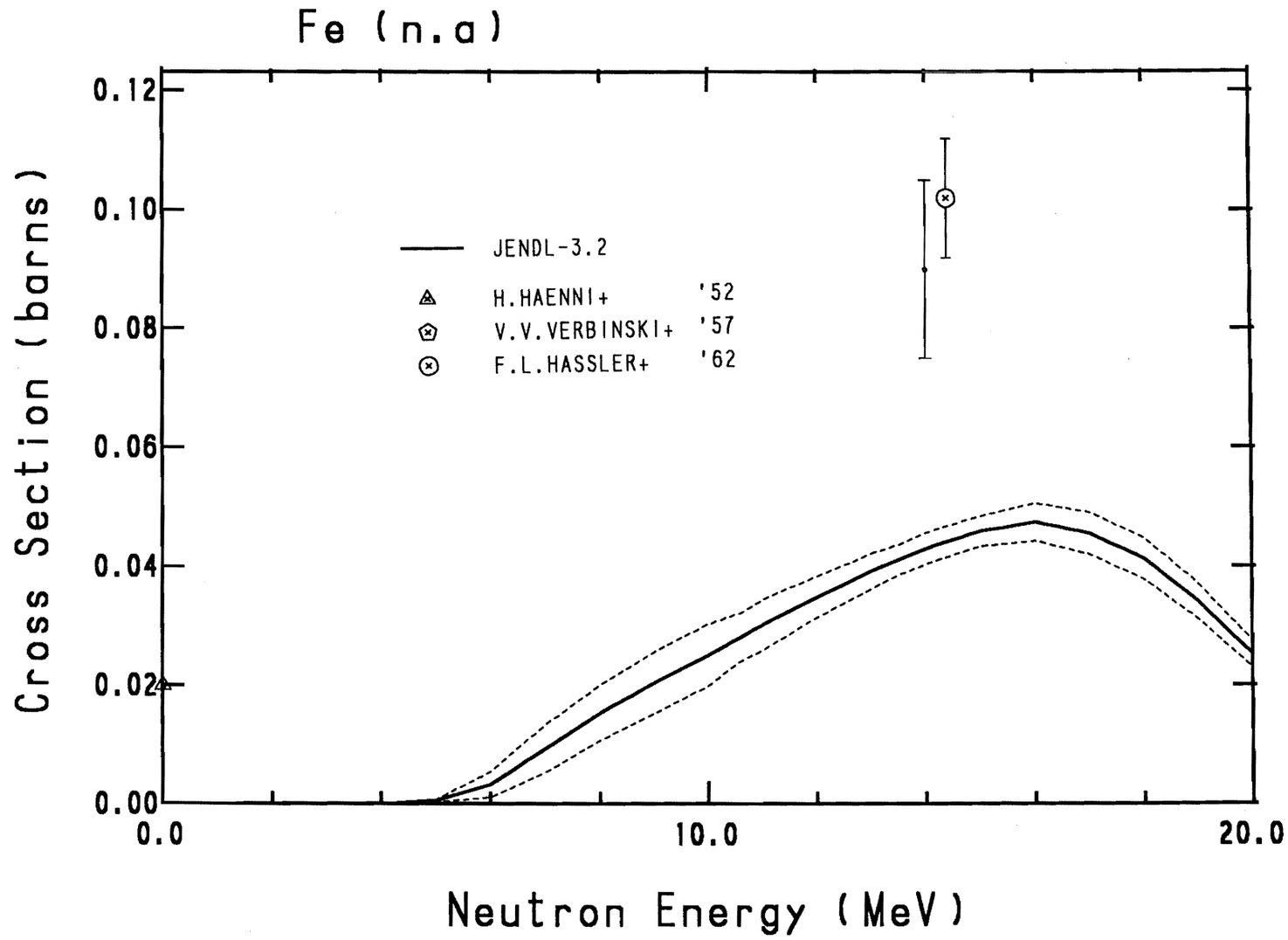

Fig. 21 (n,α) reaction cross section of natural iron.
The solid line stands for the JENDL-3.2 curve, and the dashed ones its standard deviations.

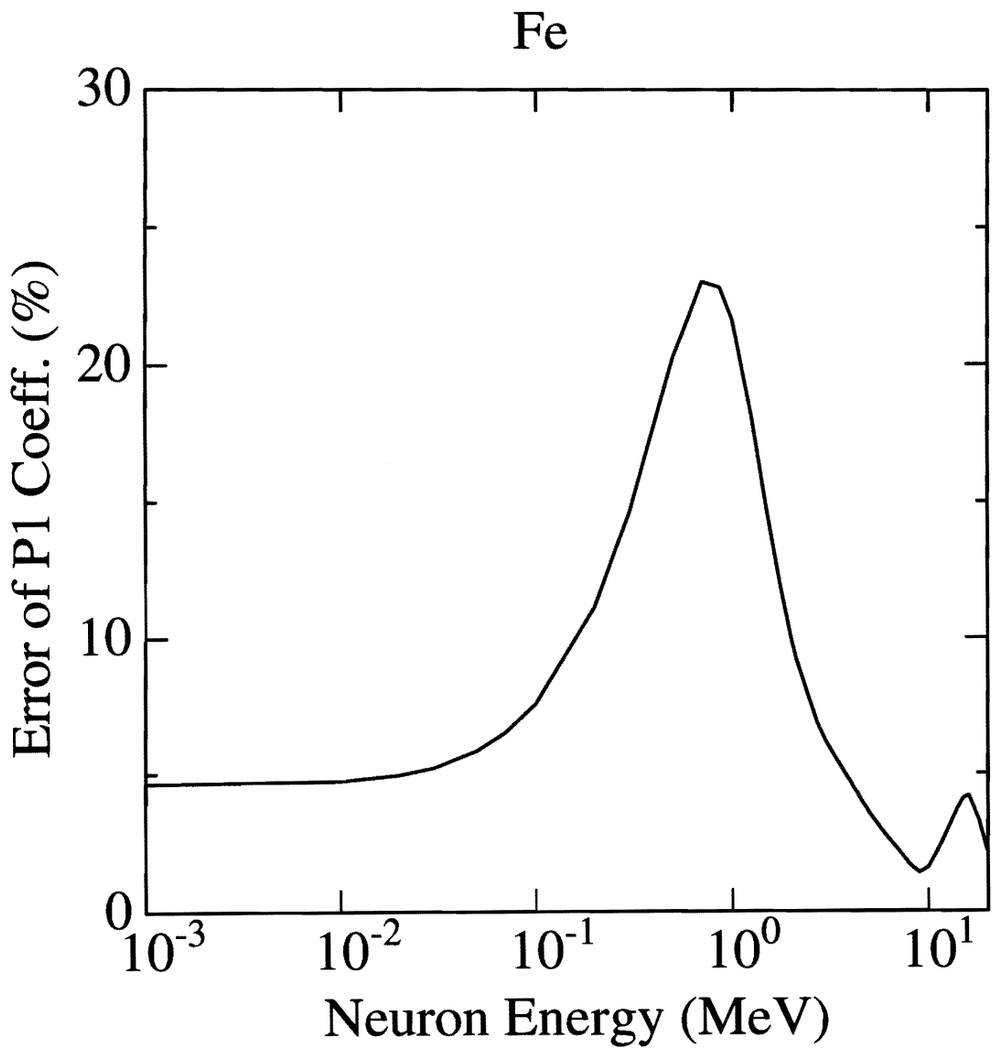

Fig. 22 Error of the 1st order Legendre-polynomial coefficient for natural iron.

U-235(n,f)

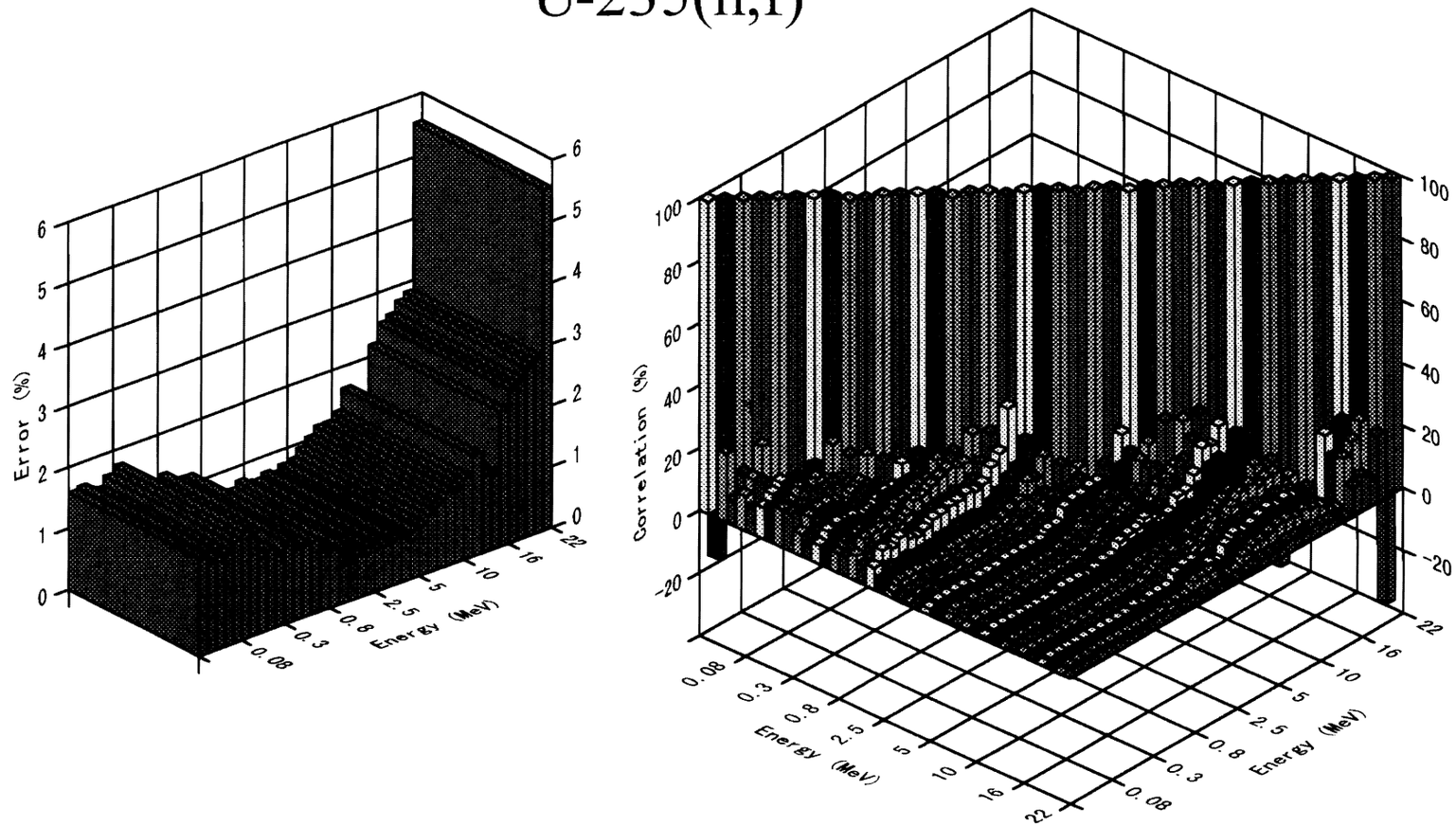

Fig. 23 Covariance of the fission cross section of ^{235}U

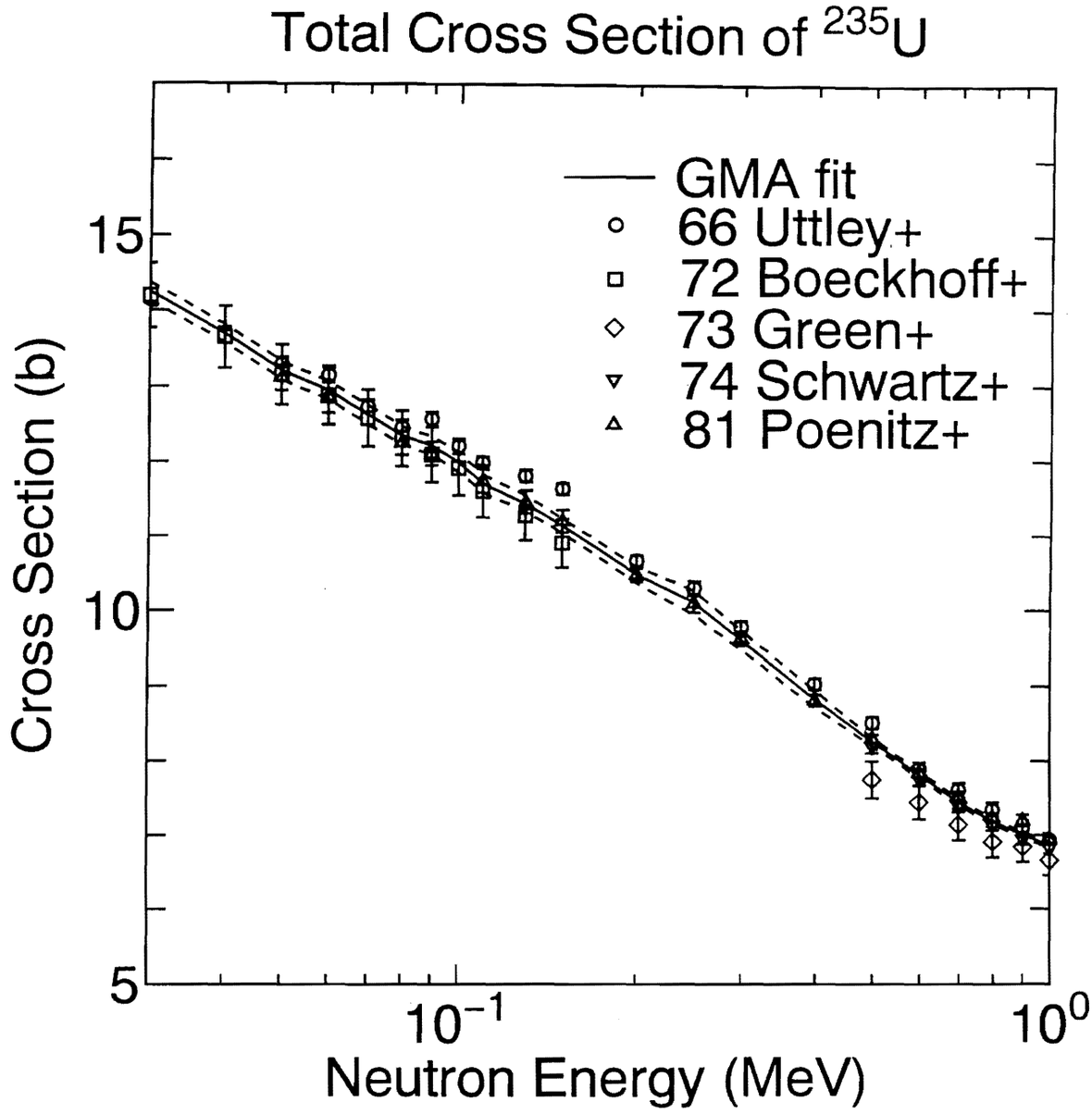

Fig. 24 Total cross section of ^{235}U below 1 MeV.
The solid line stands for the best estimate, and the dashed ones standard deviations.

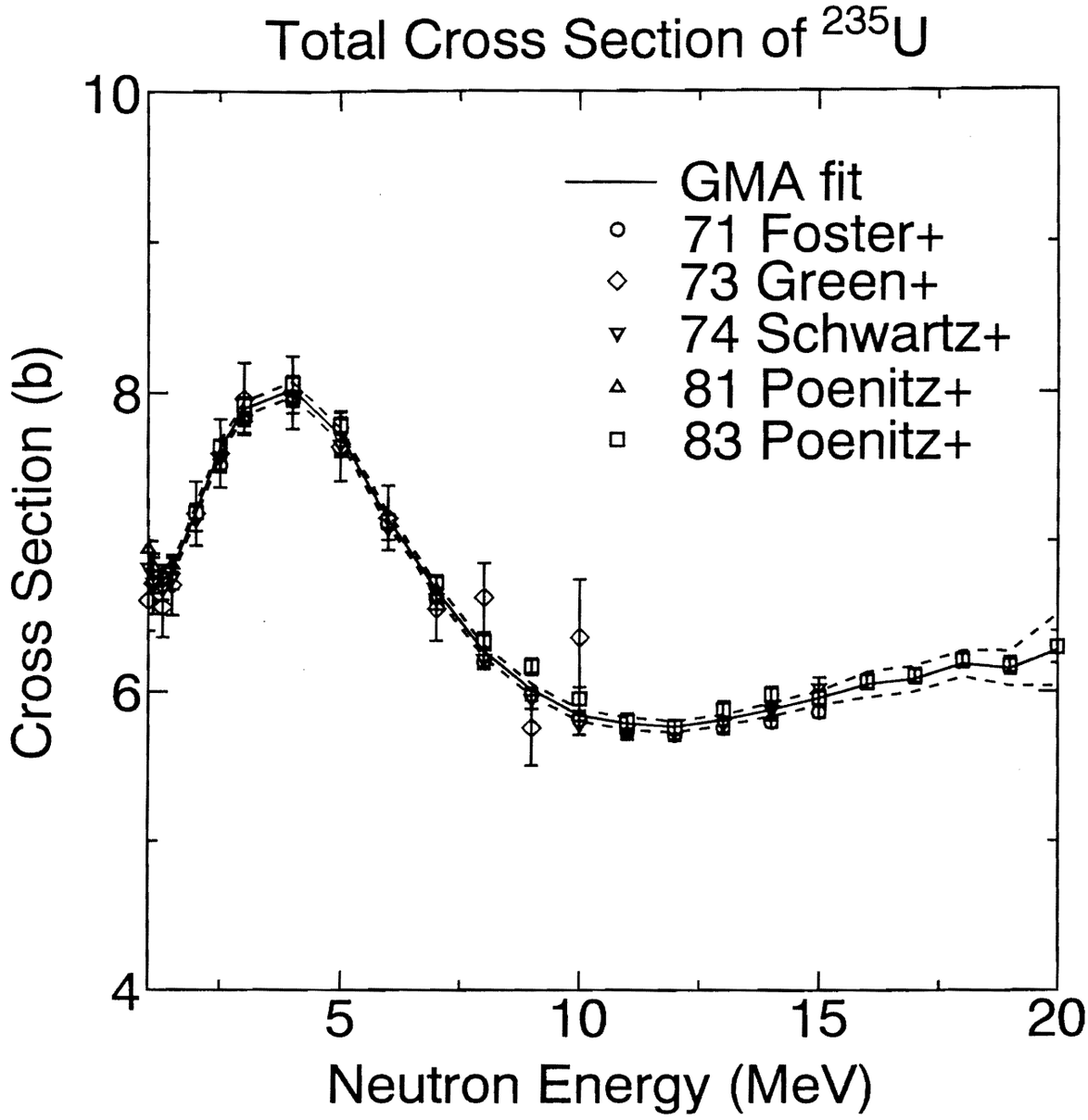

Fig. 25 Total cross section of ^{235}U above 1 MeV.
The solid line stands for the best estimate, and the dashed ones standard deviations.

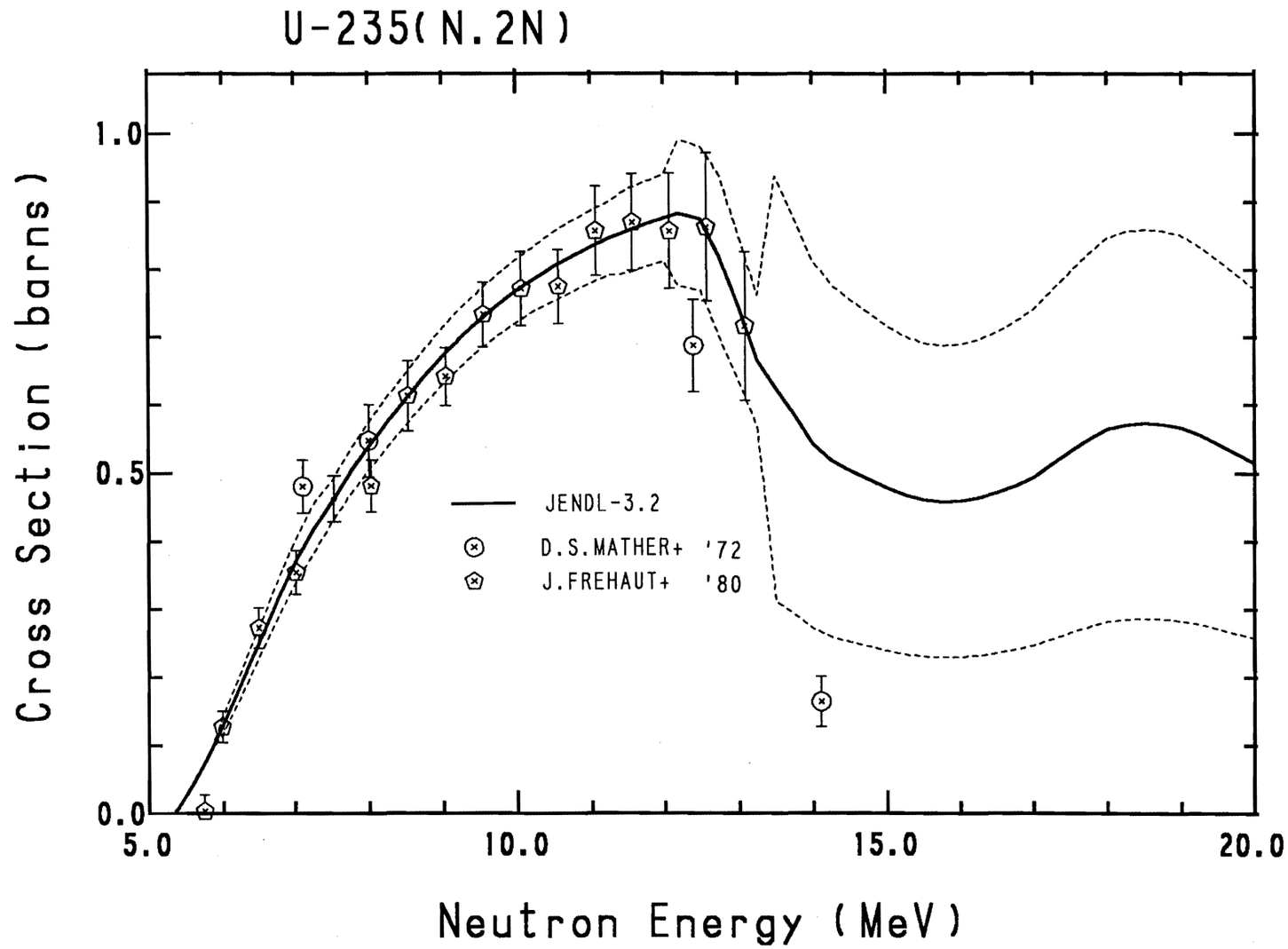

Fig. 26 (n,2n) reaction cross section of ^{235}U.
The solid line stands for the JENDL-3.2 curve, and the dashed ones its standard deviations.

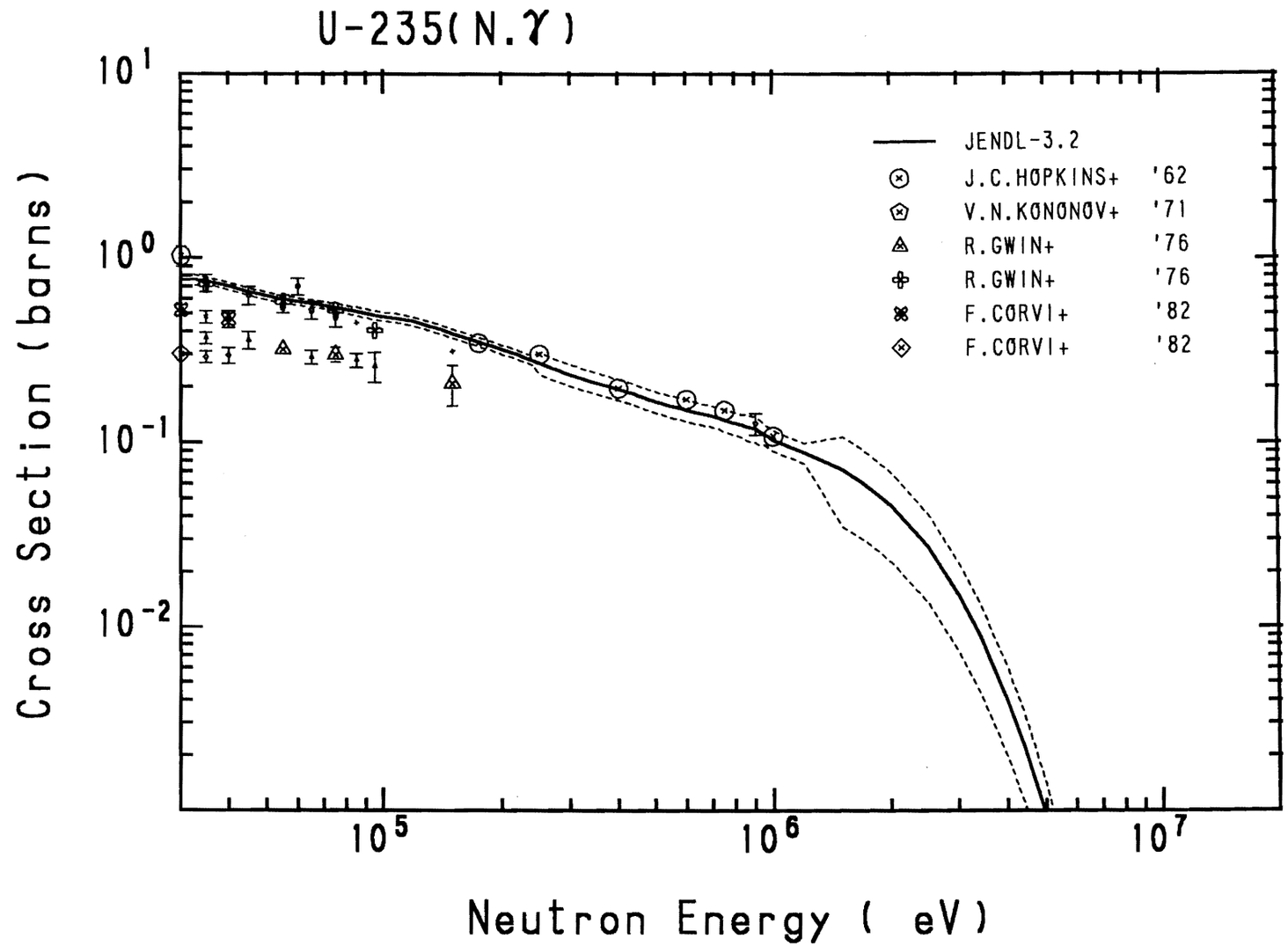

Fig. 27 (n,γ) reaction cross section of ^{235}U.
The solid line stands for the JENDL-3.2 curve, and the dashed ones its standard deviations.

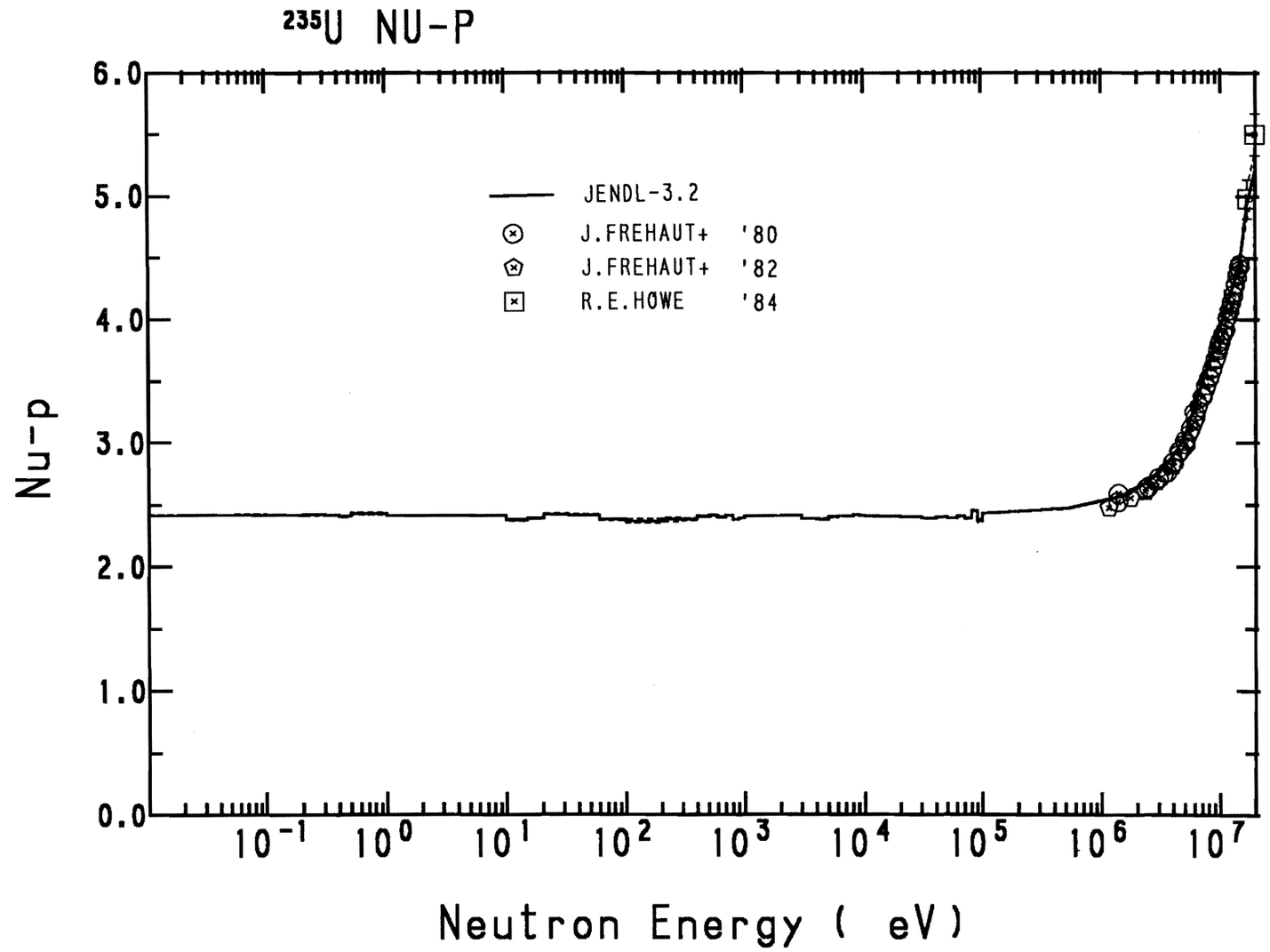

Fig. 28 Average number of prompt neutrons emitted in fission.
The errors are hardly visible, since they are less than 1%.

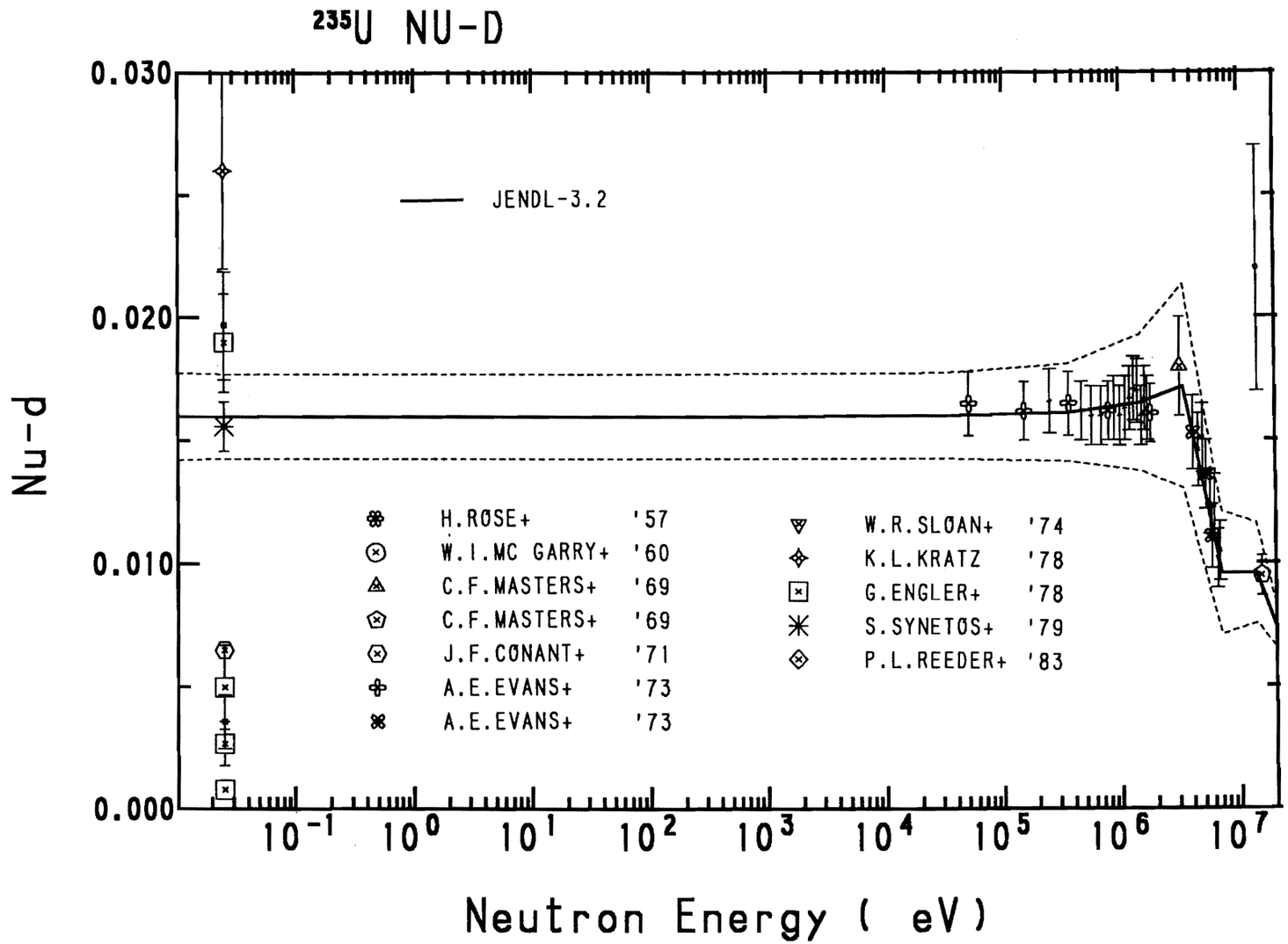

Fig. 29 Average number of delayed neutrons emitted in fission.
The solid line stands for the JENDL-3.2 curve, and the dashed ones its standard deviations.

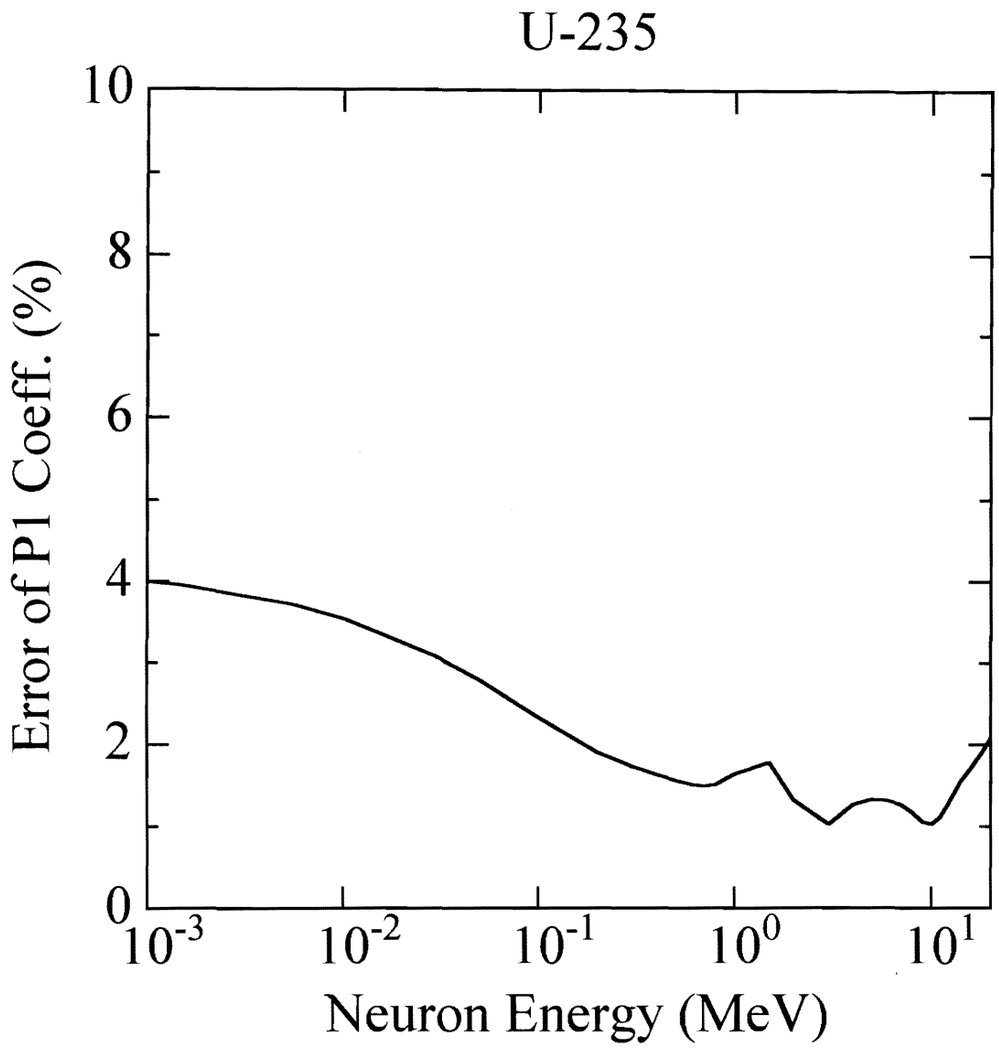

Fig. 30 Error of the 1st order Legendre-polynomial coefficient for ^{235}U.

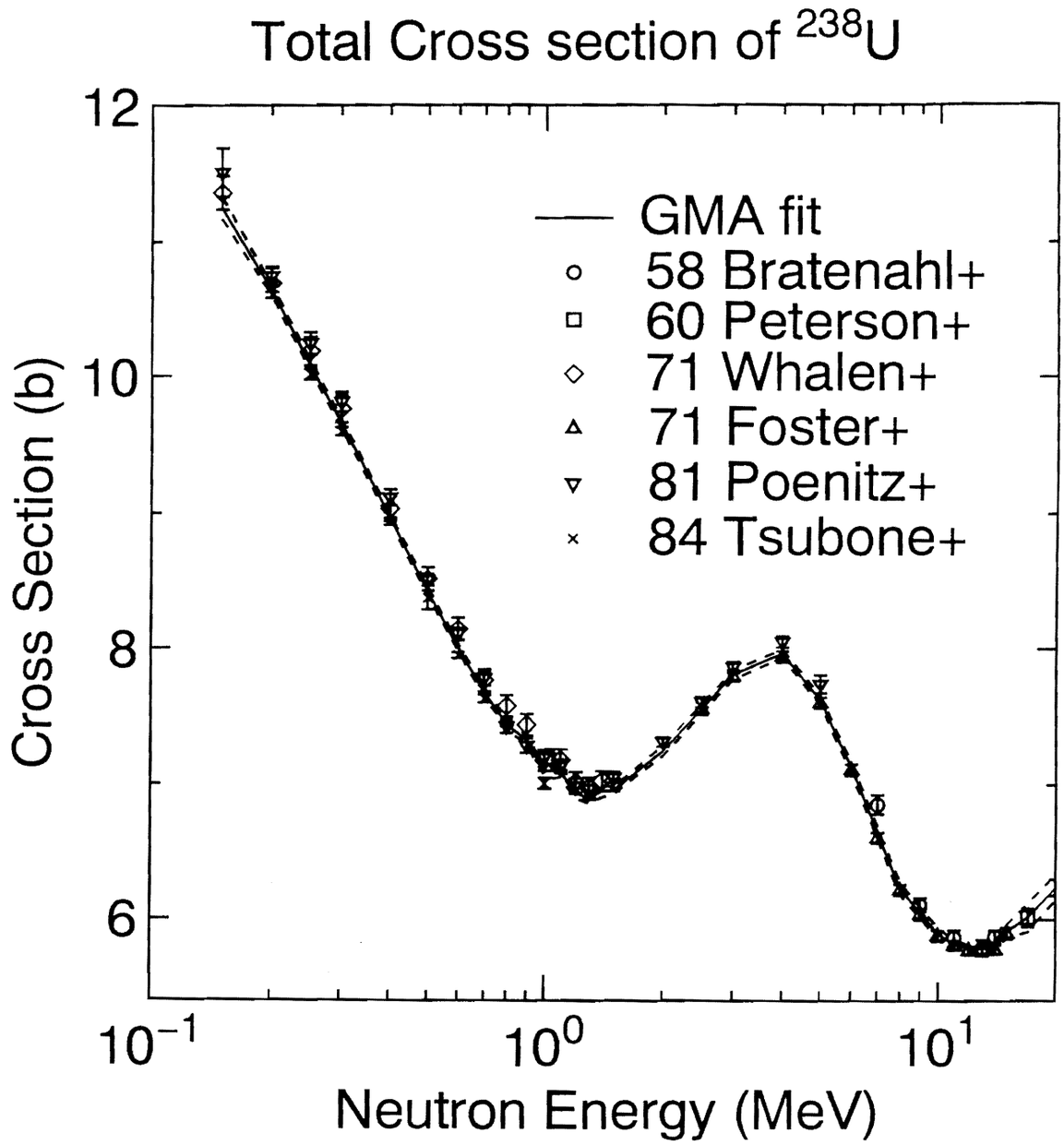

Fig. 31 Total cross section of ^{238}U.
The solid line stands for the best estimate, and the dashed ones standard deviations.

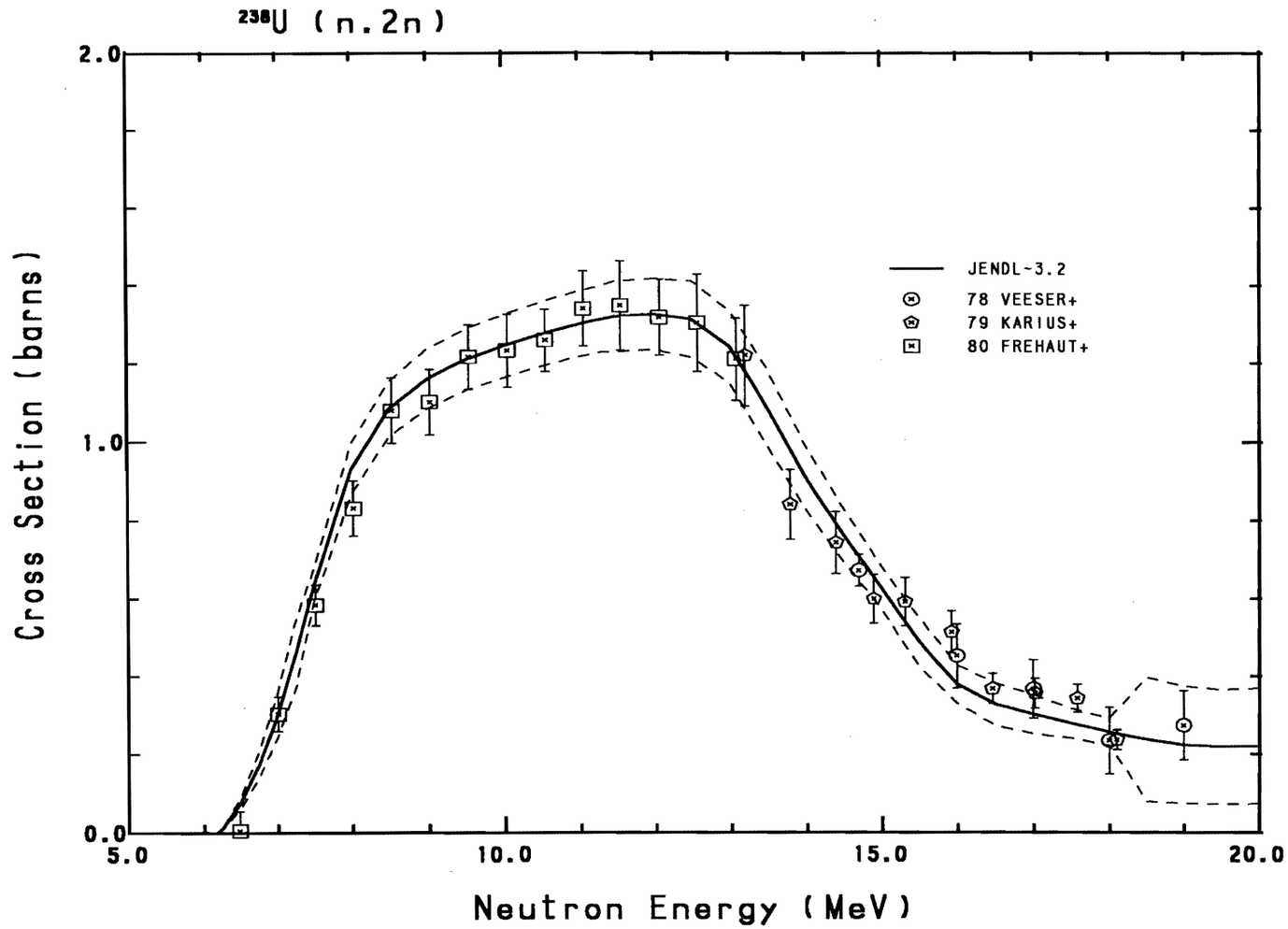

Fig. 32 (n,2n) reaction cross section of ^{238}U.
The solid line stands for the JENDL-3.2 curve, and the dashed ones its standard deviations.

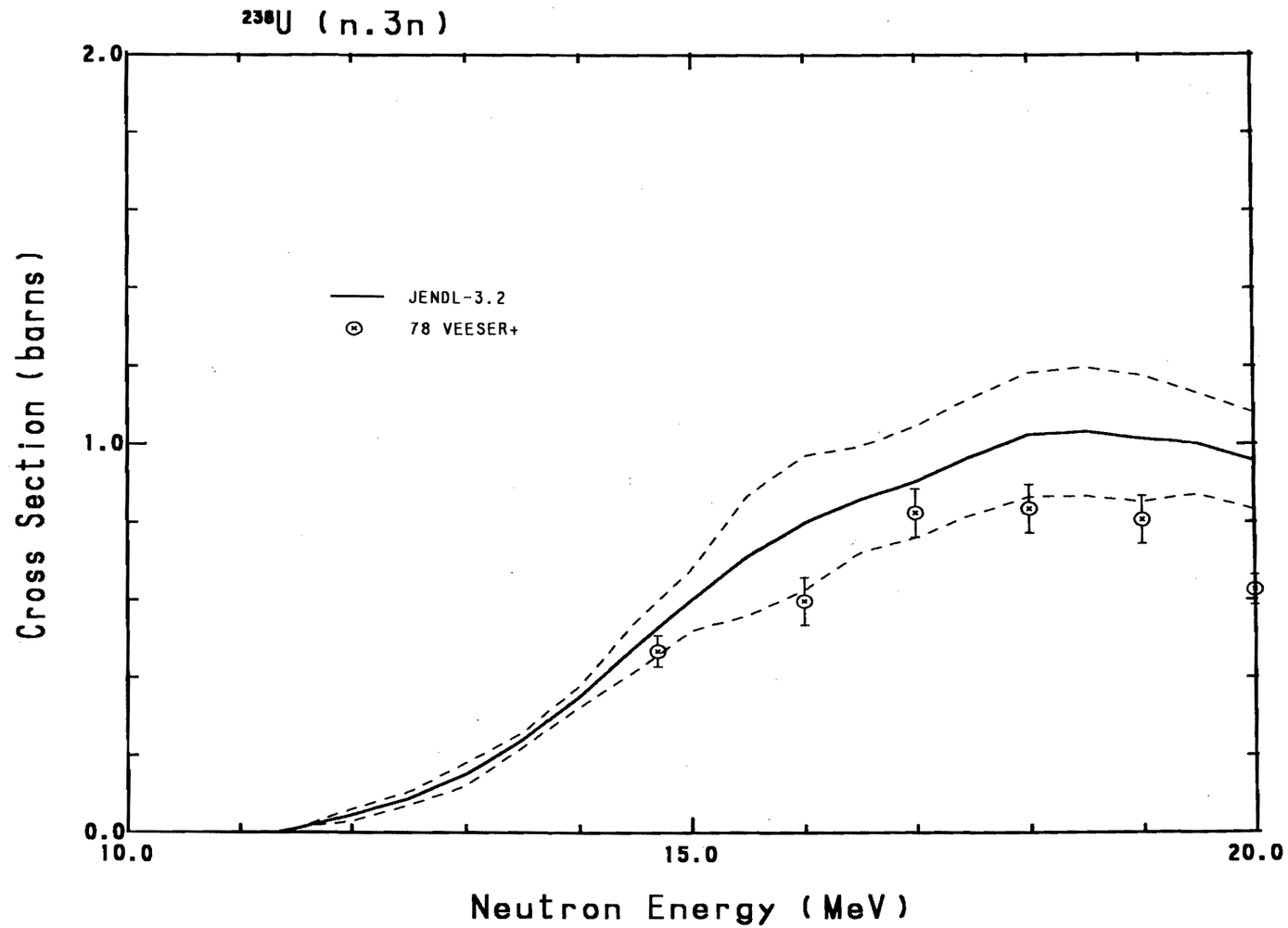

Fig. 33 (n,3n) reaction cross section of ^{238}U.
The solid line stands for the JENDL-3.2 curve, and the dashed ones its standard deviations.

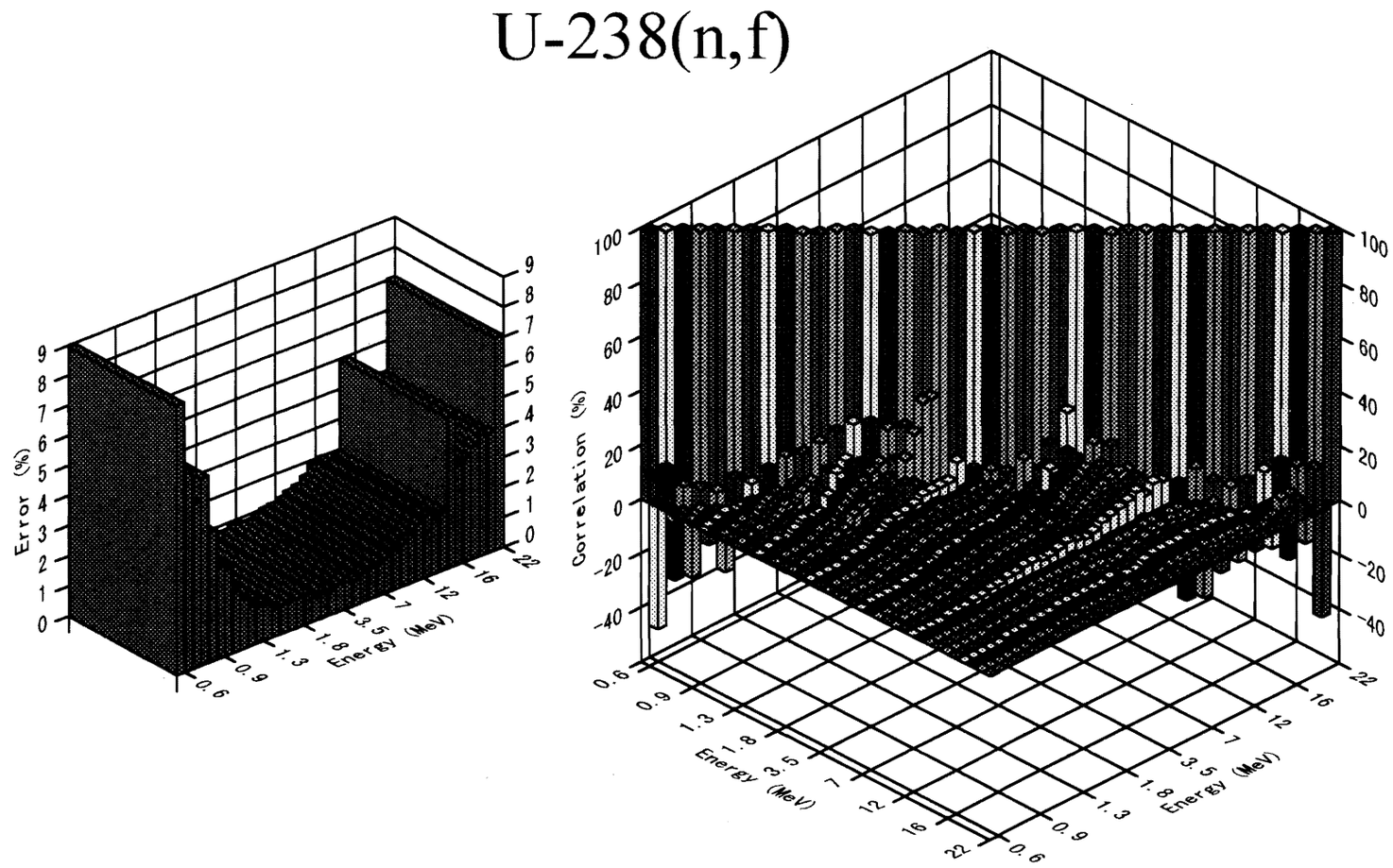

Fig. 34 Covariance of the fission cross section of ^{238}U.

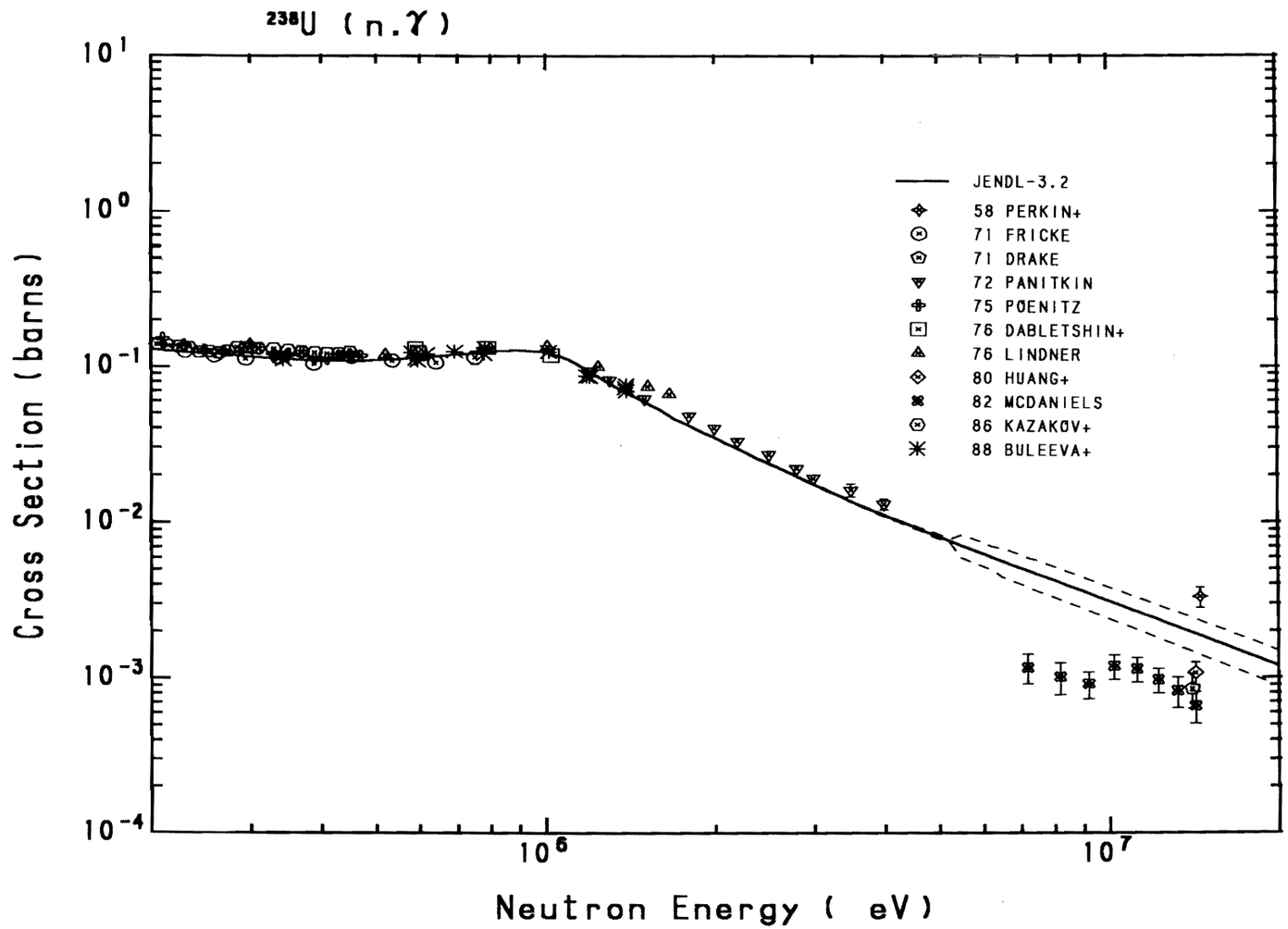

Fig. 35 (n,γ) reaction cross section of ^{238}U.
The solid line stands for the JENDL-3.2 curve, and the dashed ones its standard deviations.

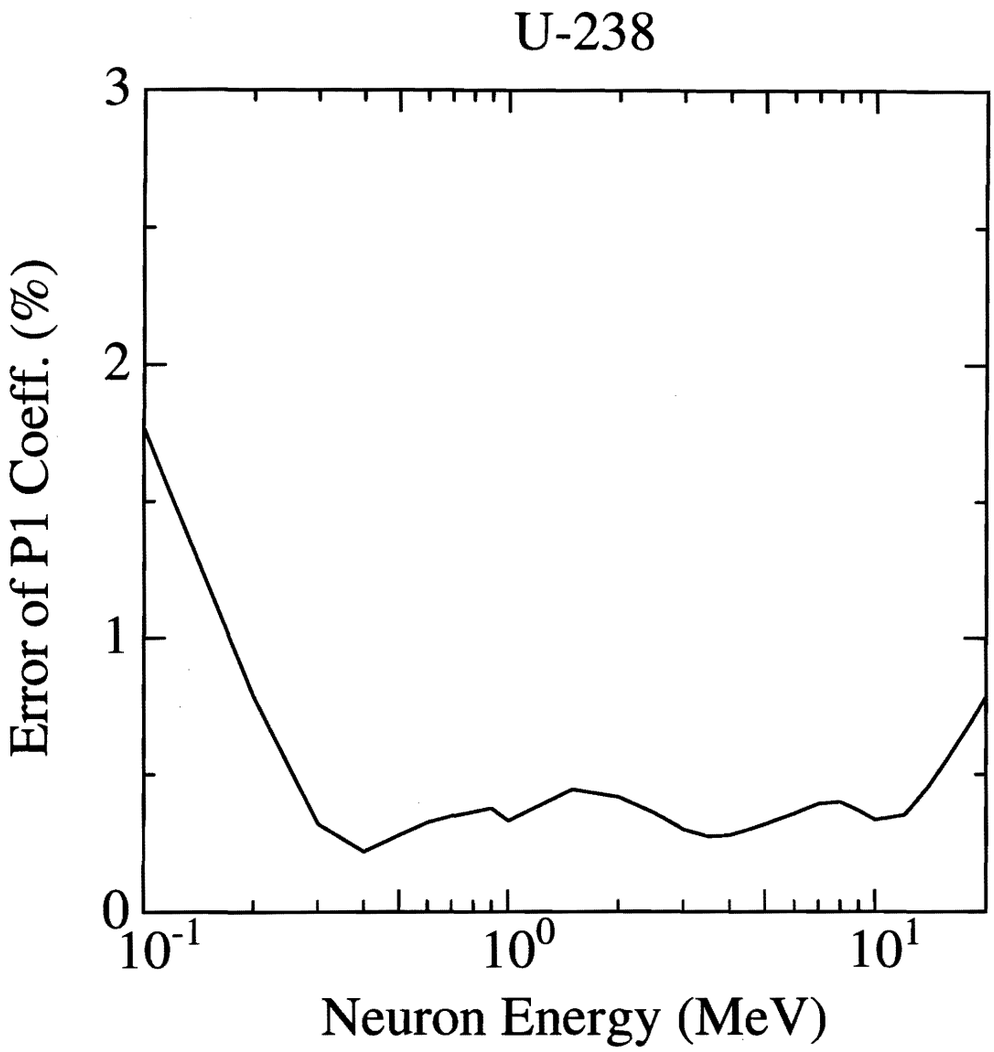

Fig. 36 Error of the 1st order Legendre-polynomial coefficient for ^{238}U.

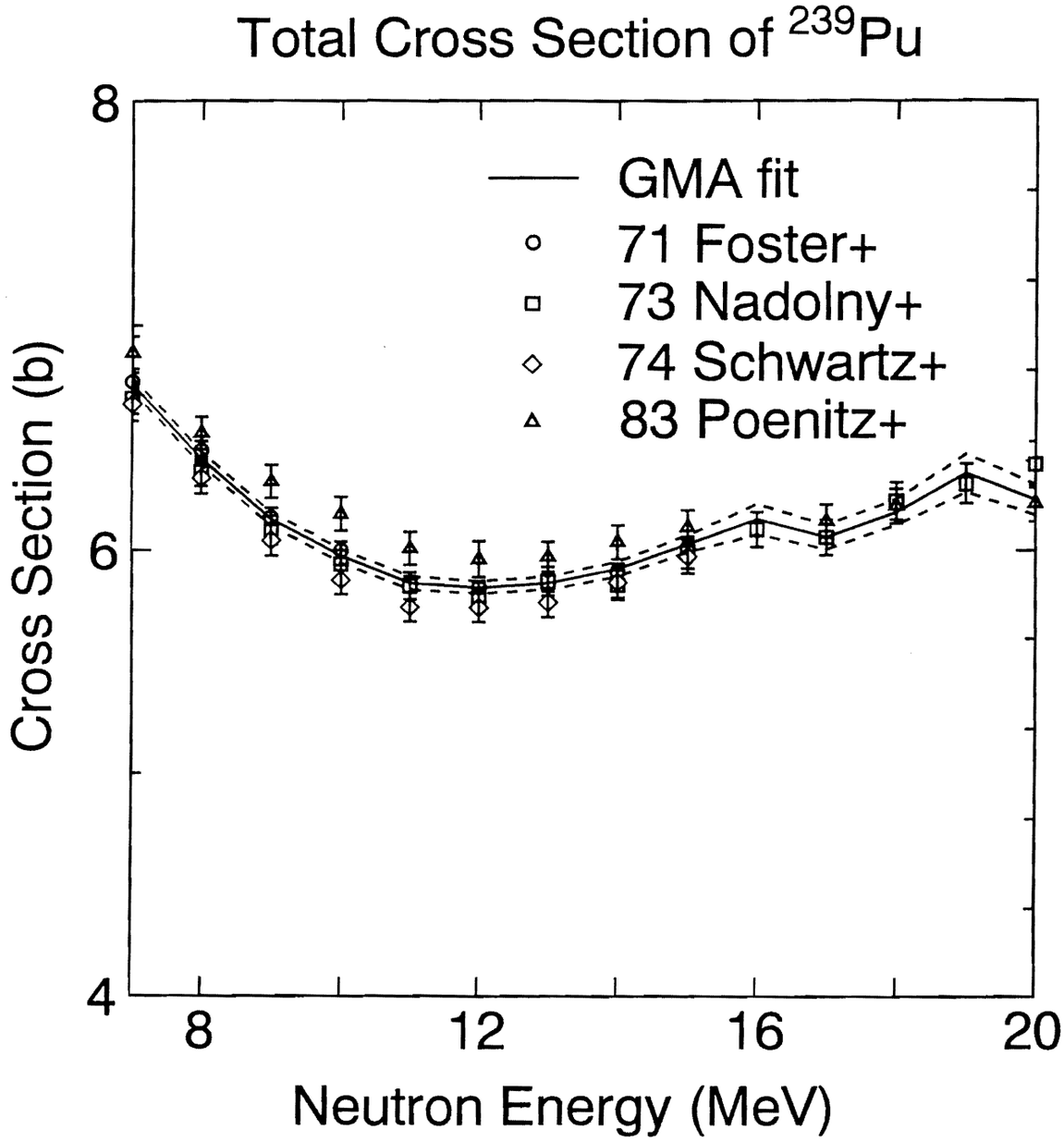

Fig. 37 Total cross section of ^{239}Pu.
The solid line stands for the best estimate, and the dashed ones standard deviations.

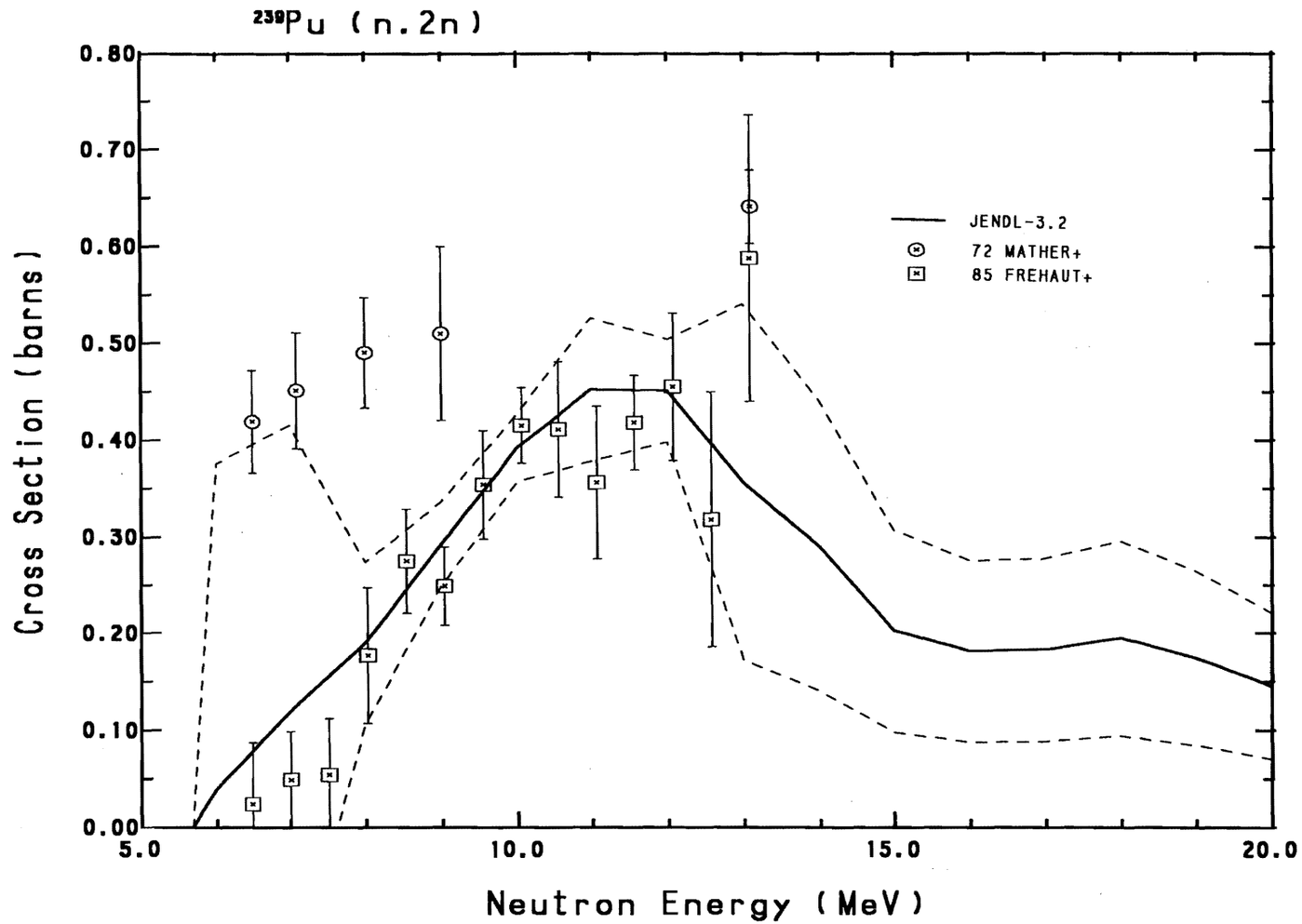

Fig. 38 (n,2n) reaction cross section of ^{239}Pu.
The solid line stands for the JENDL-3.2 curve, and the dashed ones its standard deviations.

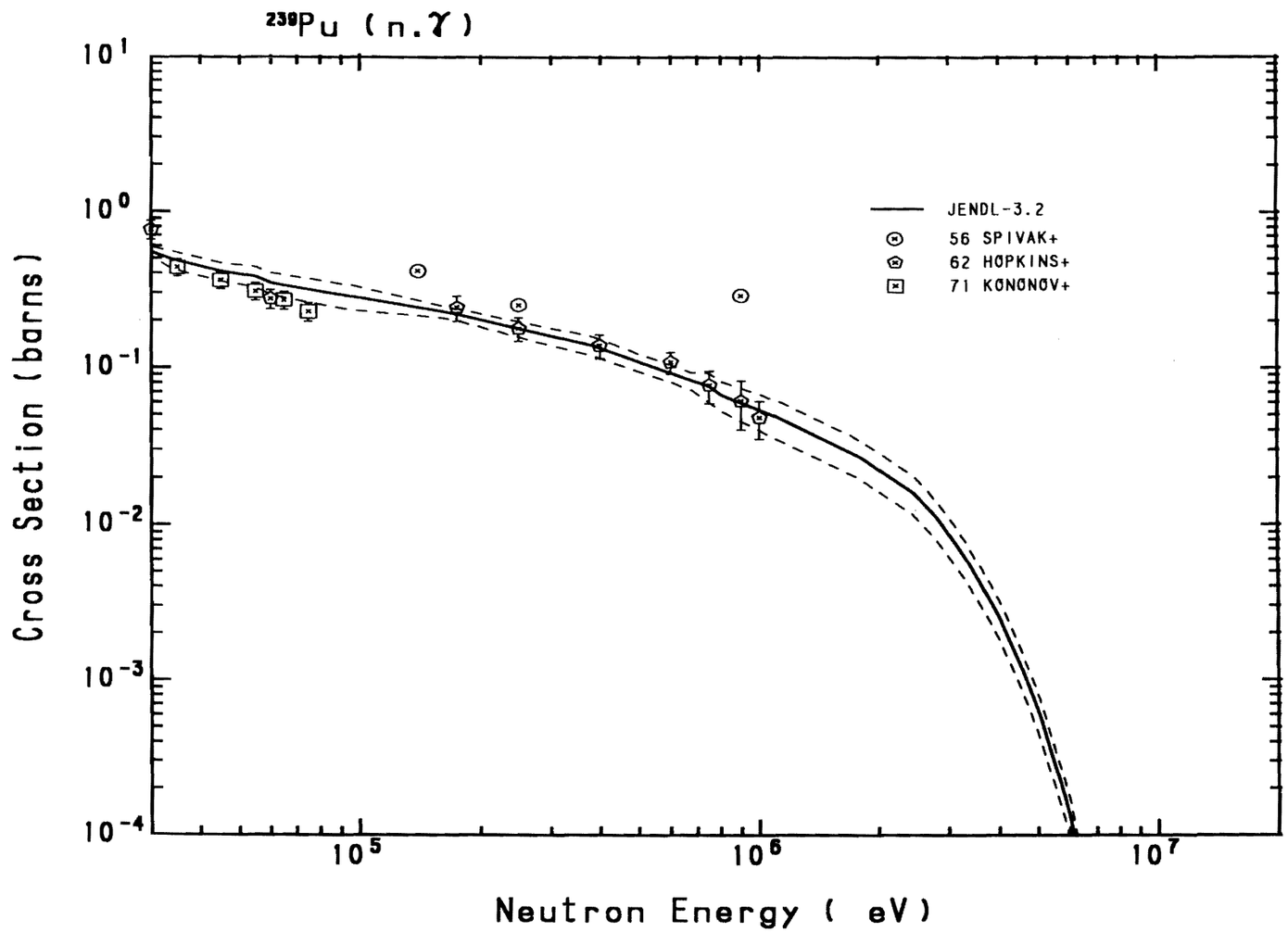

Fig. 39 (n,γ) reaction cross section of ^{239}Pu.
The solid line stands for the JENDL-3.2 curve, and the dashed ones its standard deviations.

Pu-239(n,f)

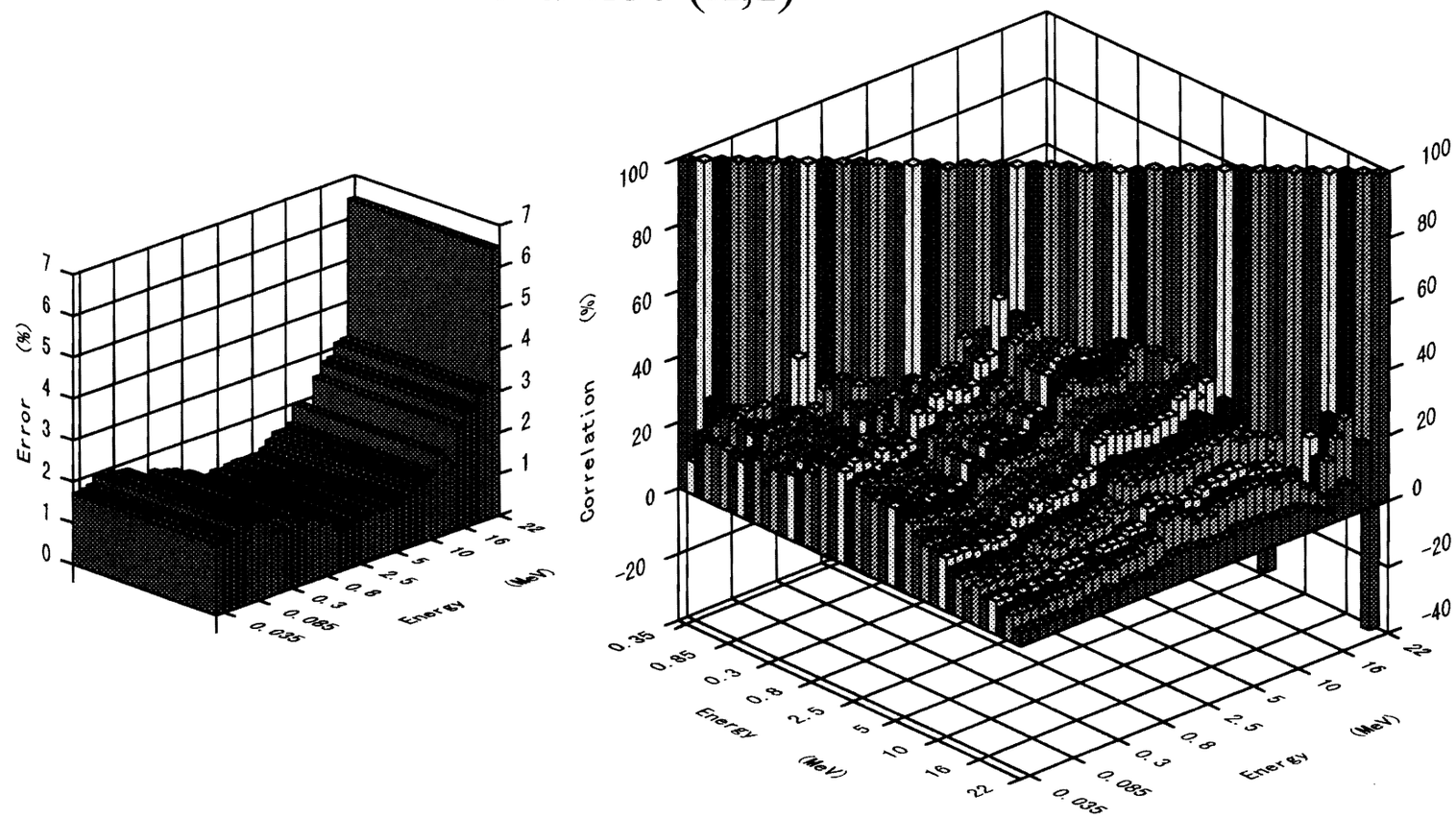

Fig. 40 Covariance of the fission cross section of ^{239}Pu

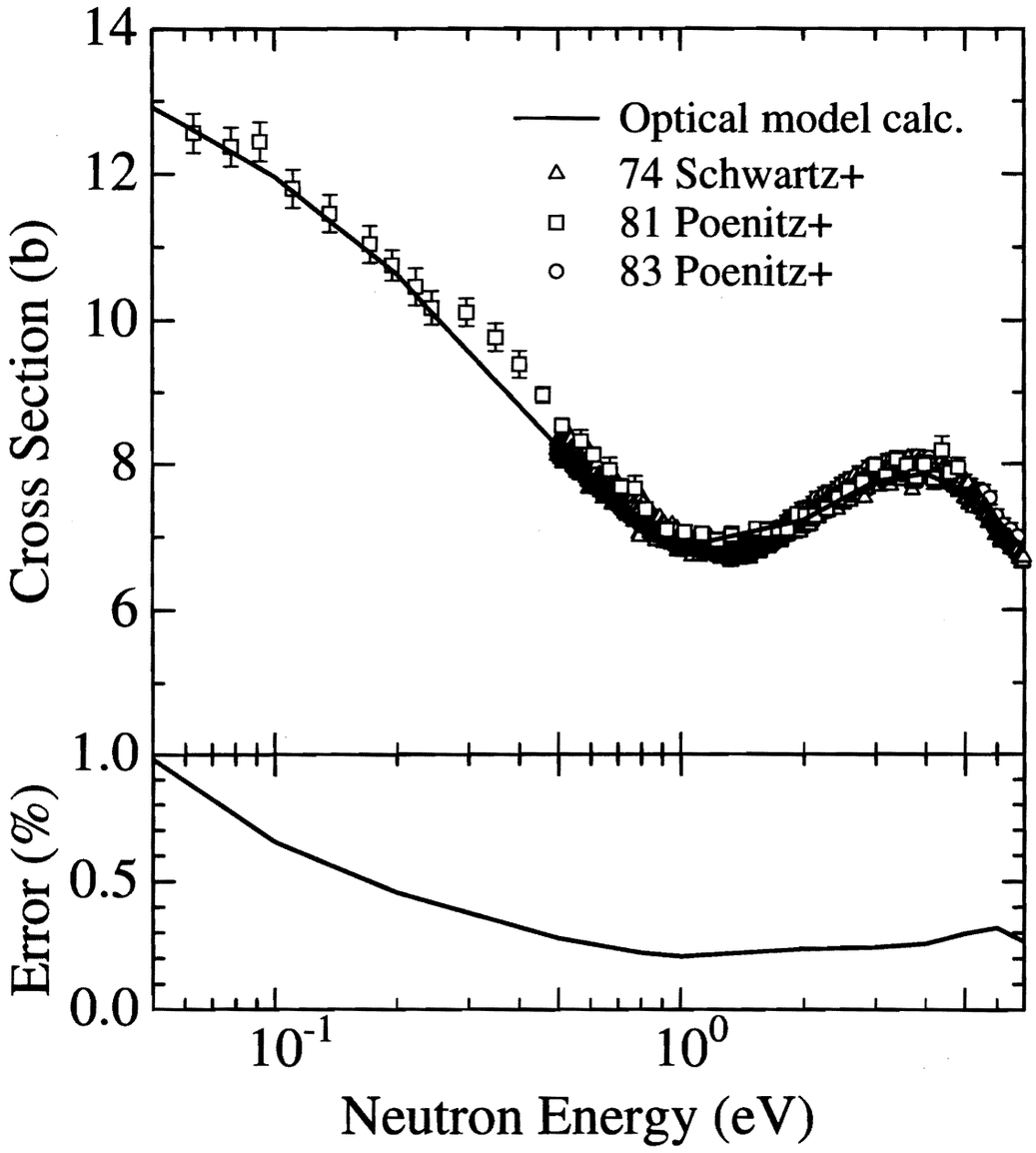

Fig. 41 Total cross section of ^{239}Pu obtained with the optical-model calculations. The lower figure stands for the uncertainties in the calculations.

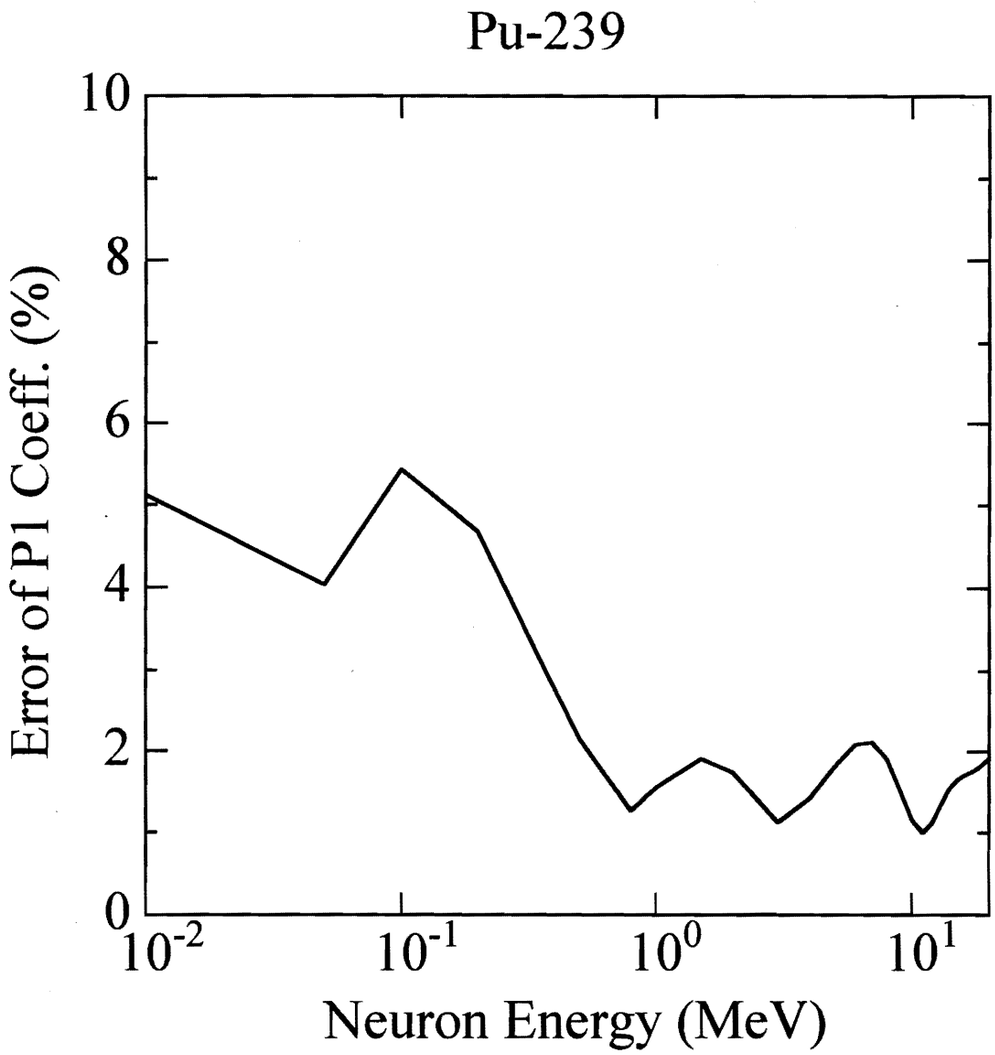

Fig. 42 Error of the 1st order Legendre-polynomial coefficient for ^{239}Pu.